DESIGN AND SIMULATION OF
CASCADED H BRIDGE MULTILEVEL INVERTER
USING GRID CONNECTED PV SYSTEM

A DISSERTATION

Submitted in the partial fulfillment of the

Requirements for the award of the degree

of

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in

ELECTRICAL ENGINEERING

(With Specialization in Electric Drives & Power Electronics)

by

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CANDIDATE'S DECLARATION

I hereby certify that work being presented in the Dissertation titled "**Design and Simulation of Cascaded H bridge Multilevel Inverter using Grid connected PV system**" is in partial fulfillment of the requirement for the award of **Master of Technology** in **Electrical Engineering with specialization in "Electric Drives and Power Electronics** and submitted to the Department of Electrical Engineering, Indian Institute of Technology Roorkee. This is an authentic record work carried out under the supervision and guidance of **Dr. S.P.Singh**, Professor, Electrical Engineering, IIT Roorkee, Uttrakhand, India.

The matter presented in this Dissertation has not been submitted by me for the award of any other degree.

24th May, 2016 **Neha Tak**

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CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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(NEHA TAK)

ABSTRACT

The continuous increase in power demands and need for a cleaner environment makes decentralized renewable energy production, like solar and wind, more and more interesting. Decentralized energy production using solar energy could be a solution for balancing the continuously-increasing power demands. This continuously increasing consumption overloads the distribution grids as well as the power stations, therefore having a negative impact on power availability, security and quality. One of the solutions for overcoming this is the grid-connected photovoltaic (PV) system.

With the extraordinary market growth in grid-connected PV systems, there is increasing interests in grid-connected PV inverters. Focus has been placed on inexpensive, high-efficiency, and innovative inverter solutions, leading to a high diversity within the inverters and new system configurations. This report chooses cascaded multilevel inverter topologies for grid connected PV systems to reduce the cost and improve the efficiency.

First, a single-phase cascaded H-bridge multilevel PV inverter is discussed. To maximize the solar energy extraction of each PV string, an individual maximum power point tracking (MPPT) control scheme is applied, which allows independent control of each dc-link voltage. A generalized non active power theory is applied to generate the reactive current reference. Within the inverter's capability, the local consumption of reactive power is provided to realize power factor correction. Then, the modular cascaded H-bridge multilevel inverter is connected to a three-phase utility system and nine PV panels. Individual MPPT control is also applied to realize better utilization of PV modules. Also, mismatches between PV panels may introduce unbalanced power supplied to the three-phase grid-connected system. Thus, a modulation compensation scheme is applied to balance the three-phase grid current by injecting a zero sequence voltage.

A modular cascaded multilevel inverter prototype has been built and tested in both the single phase and three-phase PV system. Simulation and experimental results are presented to validate the proposed control schemes. The targets of reducing the cost and improving the overall efficiency of the PV inverters can be achieved by applying the cascaded PV inverters and the proposed control schemes.

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INTRODUCTION

The primary energy used in generating electricity is about 40 percent. Out of this, the energy used for domestic purpose that is in homes and offices is nearly 70 percent which is nothing just in the form of electricity.

In all over the world the new installations of plants are becoming complicated because less availability of sites for generation, transmission and distribution. In the U.S.A., people have not been got permission since 1978 to establish nuclear power plant. The main causes for that are safety concerns, expenses during the construction as well as local opposition. If existing power plants are not relicensed at the expiration of 40 years and no nuclear power plants are built then the net power output will decrease. This decline must be replaced by other means. As gas prices are increasing day by day that means dependence will increase on coal for base load power generation. The U.S.A. has high reserves of coal but that are not fully acceptable to the public due to lack of clean coal burning technologies.

Renewable energy technologies (Wind, solar, hydro, biomass, geothermal, tidal and ocean) are an alternative to the nuclear and fossil fuel power. It is very difficult to set up hydro electric projects on large scale due to competing use of land and water. To get the relicense of existing hydro power plants, it is required to remove some of dams to protect wild life habitats. In the next decades renewable energy sources will become the only reliable energy supply due to less dependence over fossil and unclear fuels. Particularly, wind and solar photovoltaic energy conversion systems are the fastest growing renewable energy sources.

Both the solar and wind power are highly modular. The above are better in terms of economy as installations are done in stages. Even the PV is more modular than wind. It can be designed for any capacity, as the price of solar array depends directly upon peak generating capacity and indirectly upon area that is in square foot. The modularity of the wind and photo voltaic system is more important for small grids. In case of wind power plant the requirement of number and size of wind turbine is high. Without the loss of economy number of tower can be added to the existing system. Apart from that in case of existing conventional power plant expansion is neither economical not free from risk.

It is more preferable to install a new PV or wind power plant to fulfill demand in compare to laying new transmission line. In case of long overload line the voltage drop is high, so this problem can be overcome by local renewable power plant that is generation near the load. In China and India the demand is increasing day by day but apart from that these two countries rapidly growing in the field of electrical power.

Solar energy technologies are less expensive and efficient. This is an attractive solution because it is more cleaner and environment friendly than fossil fuels, coal and nuclear. Researchers are working in the field of photovoltaic to make solar energy more efficient. To make this topology more productive number of avenues exists. For example, one branch is dealing with the materials used in solar cells whereas other is finding methods to manufacture high quality silicon at lower manufacturing costs. This is the fact that energy efficiency of the solar panels affected by the high quality semiconductor material. A PV system is a combination of solar panels, battery system, DC/AC conversion circuits and other power conditioning devices.

The dissertation report I am presenting in this body of work concentrates more on the electronic means of enhancing energy efficiency in a PV system as well as converts the variable DC from sun into AC to fed AC loads. This branch of power electronics is generally called power conditioning and in the present case is used to describe the management of electrical energy to effectively charge batteries, to draw maximum power from the solar panels or provide a high quality AC output.

In case if the PV system is not constructed properly then the power output of solar panels will dissipate power as heat in the system components. In order to prevent the waste of useful electrical energy, it is necessary to develop modern methods to manage electrical power. It is advisable to increase energy efficiency as solar energy systems are more expensive in compare to other energy sources. It is beneficial to enhance the power output of renewable energy sources as they are clean energy sources, such as solar energy and they don't create pollution like traditional ones. In addition to enhance efficiency, power conditioning is also used to facilitate energy storage. For example, to provide a desired current to charge batteries it may require power conditioning circuitry. The current supplied by the PV array to the battery can be control by a DC/DC converter.

To draw maximum power from solar panels, maximum power point trackers are used. DC- DC converters are used to design circuitry for the above one. In case if load is directly connected to the solar panels and MPPT is absent then great part of electrical power may be dissipated in the form of heat. To get maximum power despite variations in light intensity and to get maximum energy efficiency, MPPTs are connected between the solar panels and load. Solar panels supply DC voltage but load side AC is required to power electronic devices. The circuitry which is used to convert the DC voltage into AC voltage is called inverter. The AC voltage can be transferred into the grid only when its frequency is 50 Hz. Hence DC voltage is converted into a 50Hz waveform with proper amplitude. The following diagram explains the use of inverter and DC/DC converter.

SOLAR PANEL

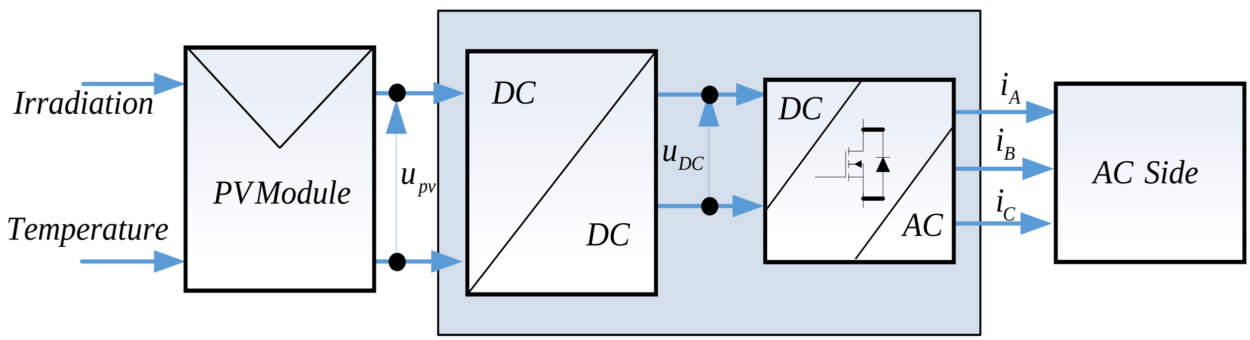


Figure 1.1:Block diagram of solar system using inverter

1.1 Objectives

PV inverter is the heart of PV system. The output of inverter contains umber of harmonics, hence to reduce the size of filter and the electromagnetic interference, the T.H.D. of output waveform should be as low as possible. Due to advantages of multilevel inverters over three level PWM inverters, it has become point of attraction for manufacturers and researchers.

In this report to reduce to improve the efficiency and to reduce the cost cascaded inverter topologies are used and to harvest more solar energy MPPT control is developed.

Firstly, the converters are connected in series under cascaded inverter topology to reach high power as well as voltage level. With the help of this topology the voltage stress on the semiconductor switches can be reduced. Thus, this is helpful to reduce the cost of PV inverters as low voltage rating MOSFETs are used and even it can be applied to large PV system. The low cost, reliability, robustness, efficiency and modularity of multilevel inverter attract the people towards this.

The better utilization of Photo voltaic module can be done without any sacrifice. Due to the above mentioned benefit cascaded H Bridge MLI can extensively be used in medium as well as large grid connected PV system. The power quality may be affected by the impact and higher penetration of PV system.

1.2 Organization of dissertation

Chapter 2- This chapter is of literature review. In this chapter grid connected PV inverter topologies as well as various PV system configurations are summarized and discussed.

Chapter 3- This chapter gives basic idea about PV systems, different types of PV systems and their applications. It also presents the topic of Matlab modeling of PV module under varying irradiance and temperature conditions.

Chapter 4- This chapter explains in detail about power conditioning system for solar PV system and the role of power conditioning elements in PV systems. It also presents the use of DC-DC converter. In addition to these controlling of boost converter is also discussed. Other than that this chapter explains in detail about the need of maximum power point trackers in power conditioning system.

Chapter 5- This chapter presents the single phase cascaded H bridge multilevel inverter for grid connected PV system. A control scheme is proposed and design calculation is given.

Chapter 6- This chapter gives idea of three phase cascaded H bridge multilevel inverter for grid connected PV system. Other than that a control scheme is proposed which gives individual MPPT control as well as to avoid the problem of shading modulation compensation is used.

Chapter 7- This chapter gives the brief idea of design procedure on FPGA.

Chapter 8- This chapter includes the simulation of solar PV module, DC-DC boost converter and single phase & three phase 3-level inverter and total PV system on MATLAB and on Xilinx System generator also.

Chapter 9- In this chapter mainly presented the way of implementation of hardware. The results from hardware are also presented in this chapter.

Chapter 10- This chapter gives conclusions of dissertation work followed by scope for future work in this area.

Chapter 2

LITERATURE REVIEW

In distribution generation systems photo voltaic systems connected to the grid play an important role. The essential element of grid connected photo voltaic system is a PV inverter which is used to convert DC power into the AC power. This AC power is further fed to the grid. To make solar power more attractive cost per inverter is important. Therefore, new system configurations are used to get high efficiency and inexpensive and innovative inverter solution. This chapter presents a literature review of present nature of the grid connected photo voltaic inverters.

To increase the PV installations, photo voltaic inverters should have following characteristics:

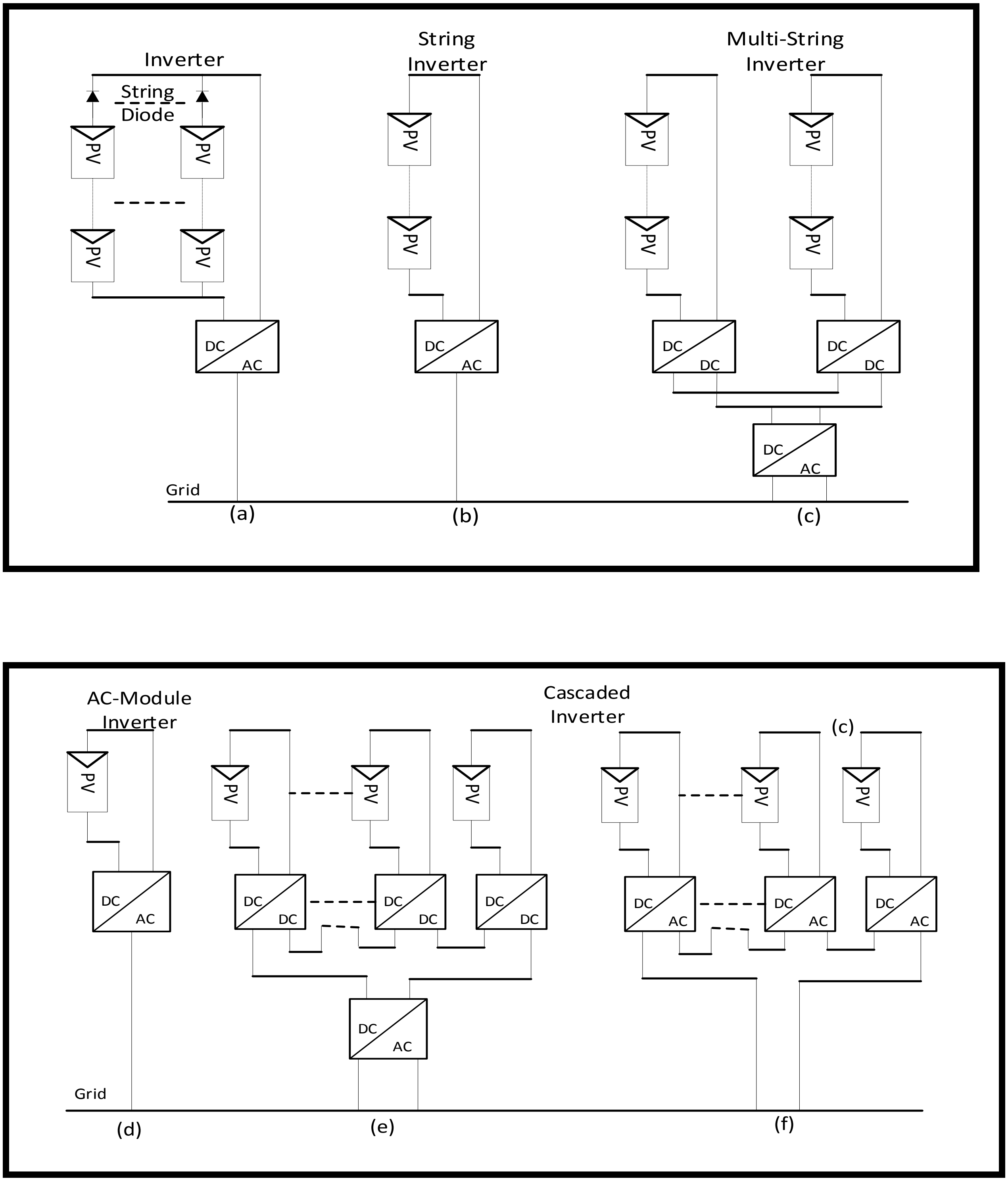
- Small size and weight
- High efficiency
- High reliability
- Low cost
- Be safe for human interaction

2.1 Overview of grid connected Photo Voltaic system

Solar electric energy demand growth is mostly in grid connected applications [1] .To increase the solar energy extraction, a maximum power point tracking (MPPT) control scheme is used which continuously tune the system. It increases the overall efficiency of the system.

Five inverter structures can be used for different configurations of PV system [2-7]:

- Central Inverters
- String Inverters
- Multistring Inverters
- AC module Inverters
- Cascaded Inverters



(a) Central inverter. (b) String inverter. (c) Multi-string inverter. (d) AC-module inverter. (e) Cascaded DC/DC converter. (f) Cascaded DC/AC inverter.

Figure 2.1: Configurations of PV systems.

The Photo voltaic system configurations are shown in figure 2.1. One PV module output is very low, so to get a sufficiently high voltage PV modules are connected in series. Along with this it also avoid further amplification. The strings are also connected in parallel through string diodes to reach higher system power level.

(a) Central inverter

Central inverters are mainly used in medium and large scale PV applications. Its power ranging starts from 10 kW. Its voltage is high enough to avoid the use of boost converters and transformers. Several inverters are shunted for high power applications [8-10].

Advantages:

- Low cost
- Simplicity
- High inverter efficiency

Disadvantages:

- Power loss due to common MPPT
- Power loss due to mismatches
- Losses in the string diodes
- Requirement of high voltage DC cables between PV panels and Inverter

(b) String Inverter

String inverters mainly used in small domestic applications. Its power ranging starts from 0.5 kW to 1 kW. It is the reduced version of centralized inverter with one string connected to an inverter useful for MPPT.

Advantages:

- No string diodes needed
- Individual MPPT for each string
- Very flexible configuration
- High system reliability
- Low cost due to mass production

- Different space orientation for each group

(c) Multistring Inverter

As shown in figure 2.1(c) multi string inverter is further development of string inverters. Each PV module is followed by DC-DC converter [11-12] and then connected to a common DC-AC inverter. It is an intermediate solution between string inverters and AC module inverters. With the help of DC-DC converter further enlargement of PV plant is possible.

Advantages:

- Flexible
- High efficiency of power extraction
- PV string is individually controlled
- Reduced power loss

(d) AC module inverter

It is a complex topology and mainly used in small scale residential applications. In this case inverter is connected to only one photo voltaic panel there is no chances of mismatching between PV modules [13-15].

Advantages:

- No mismatches losses
- Less risk of fire and arc in DC wiring
- Flexible design
- Independent function of each module unit

Disadvantages:

- Low overall efficiency
- Requirement of high voltage amplification
- Price per watt is high
- Complex circuit topologies

(e) Cascaded inverter

When several converters are connected in series to get high output voltage is known as cascaded inverter. This module is a combination of AC module inverter and string inverter [16-18]. Each PV module contains its DC-DC converter and again these modules along with their converters are connected in series, which further gives High DC voltage.

Advantages:

- Individual module MPPT
- Cheaper and efficient than AC module inverter
- Better utilization per PV module
- Redundancy of system
- No requirement of per string DC bus and inverter
- Controls grid current and reactive power compensation

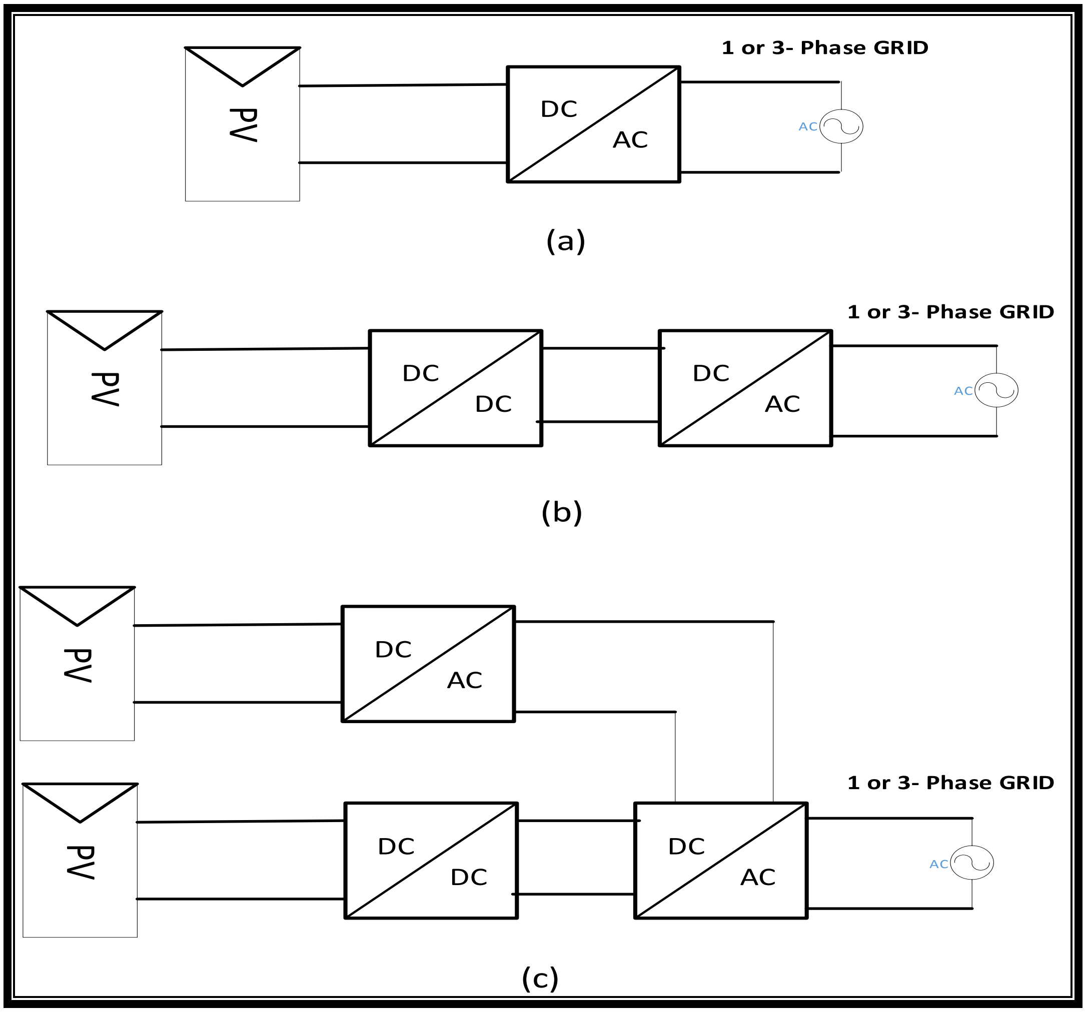
2.2 Topologies of grid connected PV inverter

Grid connected photo voltaic inverter topologies can be divided as follows:

- The number of power conversion stages
- With or without transformer
- The use of decoupling capacitors

Further it can be categorized on the basis of power processing stages. These stages are as shown in below figure 2.2. These stages are:

- Single stage inverter
- Dual stage inverter with single DC-DC converter
- Dual stage inverter with multiple DC-DC converter



(a) Single stage inverter (b) Dual stage inverter with single DC-DC converter
(c) Dual stage inverter with multiple DC-DC converter

Figure 2.2: Three cases of multiple and single stage inverter

2.2.1 Single stage inverter

The configuration of single stage inverter is shown in figure 2.3. Full bridge inverter is mainly used in single phase system. The main advantage of single phase inerter is that it does not required additional devices hence; there is no high cost, conduction losses and sluggish transient response like two stage inverter.

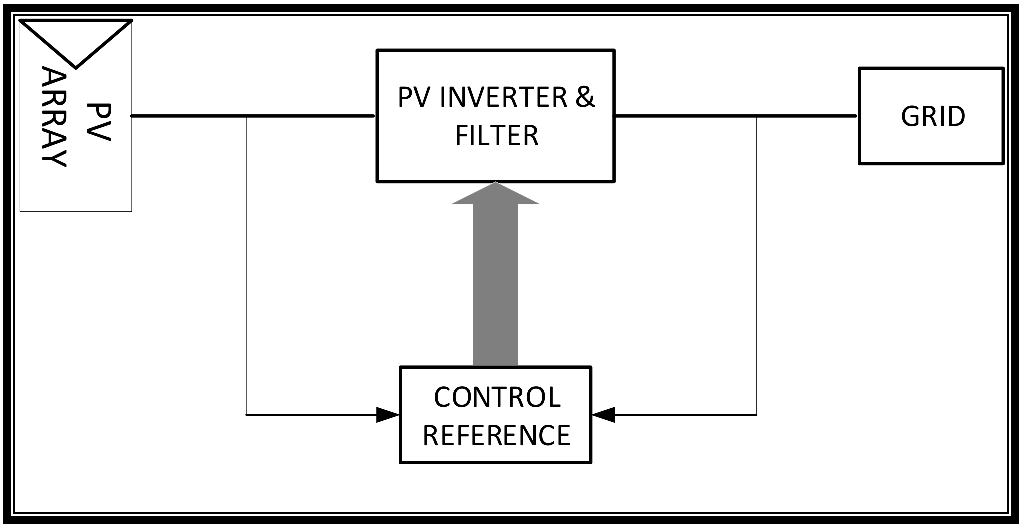


Figure 2.3: Power electronic system

Advantages:

- High efficiency
- Low price
- Easy implementation

Disadvantages:

- Due to shading effect on PV panels it can affect the efficiency of the system.

2.2.2 Two stage inverter

Dual stage inverter is a combination of DC-DC converter and Inverter circuit. The dual stage topology is shown in the figure 2.4. In this topology the DC-DC converter is working as a boost converter which performs MPPT as well as voltage amplification and inverter is playing an important role to control grid current.

At first stage boost converter is used to provide fixed DC voltage and at the second stage voltage source inverter is used in the single or three phase system. This topology removes the requirement of transformer at load side. Hence this is cost effective technique which also increases the efficiency of the system.

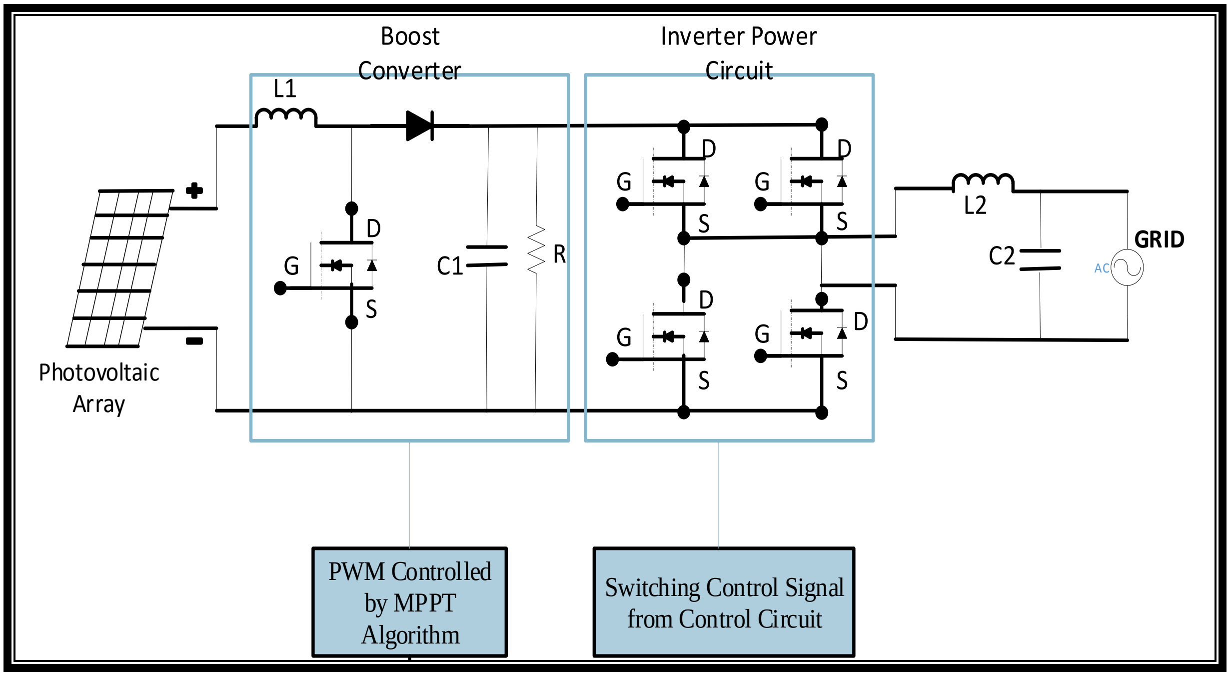


Figure 2.4: Two stage topology

2.3 Comparison of various methods

A PV inverter is the heart of grid/load connected PV system and it is used to convert DC power from the solar panels into AC power fed to the grid. There are three type of multilevel inverter topologies which are basically used now days. These are Neutral point clamped (NPC), Cascaded H Bridge (CHB), Flying Capacitor (FC).

The cascaded H Bridge has many features which make it superior than others like its modularity and simple layout. It does not required extra clamping diodes or capacitors like remaining two. It also allow transformer less connection which make it modular in nature [19].

The CHB-MLI like other multilevel inverter topologies, gives staircase AC output waveform with less THD in compare to 2-level inverters. Using multicarrier techniques [20-21] the above thing can be carried out either at fundamental frequency or at higher switching frequency.

Modular Cascaded multilevel topology improves efficiency and flexibility of PV system. In Cascaded multilevel inverter several single phase inverters are connected in series and each PV panel is connected to its own DC/AC inverter. This topology is favorable for medium and large grid connected PV system as it gives [22-23] high power and high voltage from the combination of no. of modules. Grid/load connected PV system generally uses 2 stages [24-25] to feed solar power into the grid. The first stage is of boost converter which is used to boost the PV voltage and track the maximum solar power. The second stage is DC/AC inverter which is particularly used for inversion of power.

The CHB consists of several DC links connected to PV strings individually and with independent MPPT [26] which is its major advantage but in case of three phases the problem of PV mismatches may occur. It leads to unbalanced supply power leading to unbalanced current. Above problem can be sort out with the help of various compensation techniques [27]. Most of the research is going on in the field of single phase solution [28-32] because there is a great drawback of CHB-MLI that is power imbalance. One of the solutions proposed in the literature [33]. In this method to make unbalanced current the neutral of reference voltage is shifted. This is also known as feed forward compensation.

In past [34], the balancing achieved through a redundancy based strategy but afterwards it uses simple PI controller combinations. This solves the problem related to stability. The grid current should be in phase with grid voltage to maintain stability. This requirement can be fulfilled by using a PLL [35] which used "Virtual flux" based synchronization. All of these papers [36-37] assumed that the dc sources are equal and do not vary with time. In [38-39] analytical solutions have been derived for the condition of unequal dc sources. But all the above techniques used are time consuming. Therefore to store the results in a look up table and to calculate the solution of switching angle offline an alternate approach [40-41] has been determined. Even then, the solution could be missing for some operating point.

To resolve this problem, the ANN [42] replaced the look up table. It is faster than others and real time control can be easily established. In CHB-MLI large numbers of inverters are required to reduce the harmonics. Apart from that a complex DC voltage regulation method has to be used to control the output voltage of STATCOM [43]. A new type of method [44] is proposed to solve the above problem of current harmonics which occurs due to ripple voltage.

2.4 Conclusion

A literature review on PV inverters which are connected to grid has been discussed. Other than that grid-connected PV inverter topologies are also discussed. The inverter topologies can be divided on the basis of power processing stages and these are single stage and dual stage inverters. Many topologies related to single as well as dual stage inverter have been reviewed. Comparison have done between different topologies to get better results.

Chapter 3

PHOTO VOLTAIC SYSTEM

A PV solar cell or module converts solar energy into electrical energy. Solar cell is the basic part of solar panel and a solar PV module is formed if many cells are connected in parallel and series. PV systems are combination of solar arrays, power conditioning devices and load [45].

Photo voltaic system applications:-

1. Stand alone PV systems
    - Consumer applications
    - Simple house systems
    - Residential systems
    - Hybrid systems
2. Grid connected PV system
    - Decentralized grid connected systems
    - Centralized grid connected systems

3.1 Stand alone PV systems

The areas which have no access to an electric grid normally used stand alone PV systems. In standalone systems the energy produced from PV module being stored in batteries. These systems are also known as isolated systems.

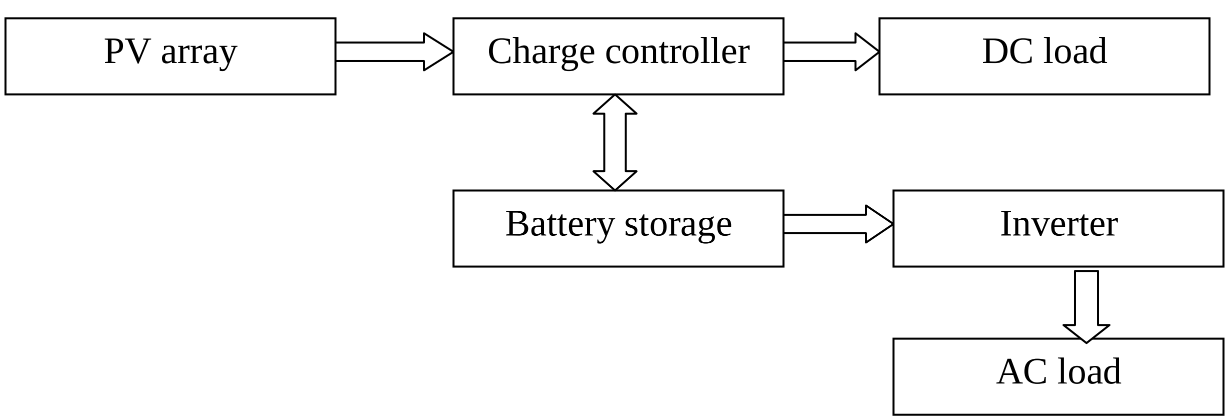
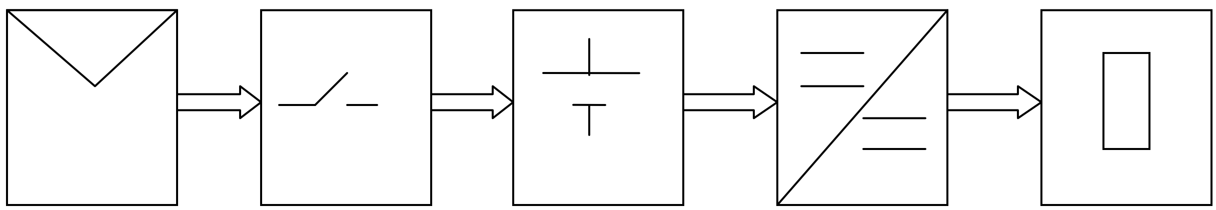


Figure 3.1: Schematic diagram of a standalone PV system

3.1. 1 Consumer applications

The first consumer application was solar calculators. As no storage require the above one is an ideal application. The other products which are available with solar power are watches, battery chargers etc. All the products consist of small PV modules, DC-DC converter, energy storage unit and a charge controller.



PV generator | Charge Controller | Energy Storage unit | voltage conversion | Consumer

Figure 3.2: Block diagram of PV power supply for a small consumer product

3.1.2 Solar home system

A solar home system consists of the solar generator, led battery and charge controller and DC appliances as a load. For the appliances support structures are also needed which are sockets, cables and module.

The benefits of solar home system compared to traditional energy sources used for lightening are as follows:-

- Improvement in illumination quality
- No health risk that is smoke and smell
- No risk of fire hazard
- Long lifetime
- Less expensive than traditional one

3.1.3 Residential system

Stand alone systems supply electric power to buildings. PV is very economic alternative to a diesel engine when there is no connection to the grid. For residential system AC power is required. Therefore, it also consists of inverter to convert DC into AC. Stand alone PV systems which supply electrical energy to buildings must also have storage battery as radiation intensity changes with season and weather conditions. The schematic diagram of standalone PV system supplying to residences is given below:-

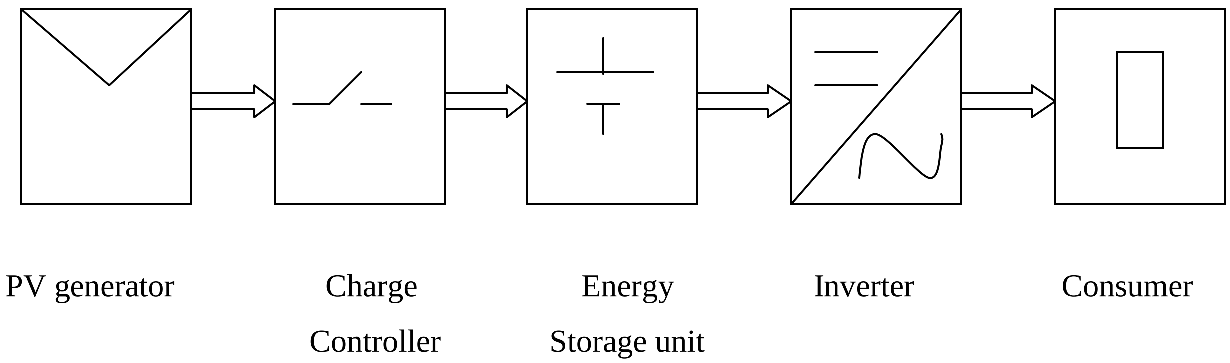


Figure 3.3 : Schematic diagram of standalone PV system supplying to residences

3.1.4 Hybrid systems

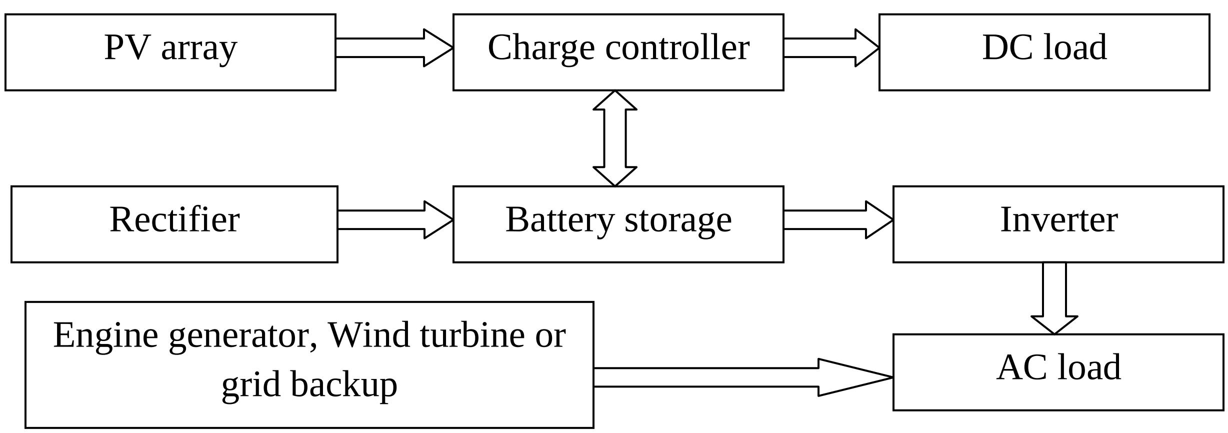


Figure 3.4 : Schematic diagram of a hybrid system

When more than one electricity generators are employed then the system is known as hybrid system. The other type of generators can be renewable that is wind or conventional such as diesel engine or the utility grid. The schematic diagram of hybrid system is shown in figure 3.4.

3.2 Grid connected PV system

As technology is increasing people are attracting towards grid connected photo voltaic system. In this the utility power that is power from the grid is automatically provided at night as well during the day when demand exceeds the solar power generation. That means during the day the electricity generated from PV system can be immediately fed to the respective loads or it can be sold to the electricity supply companies.

For grid connected photo voltaic system battery storage is not required. A schematic diagram of grid connected PV system is shown in figure 3.5 [46].

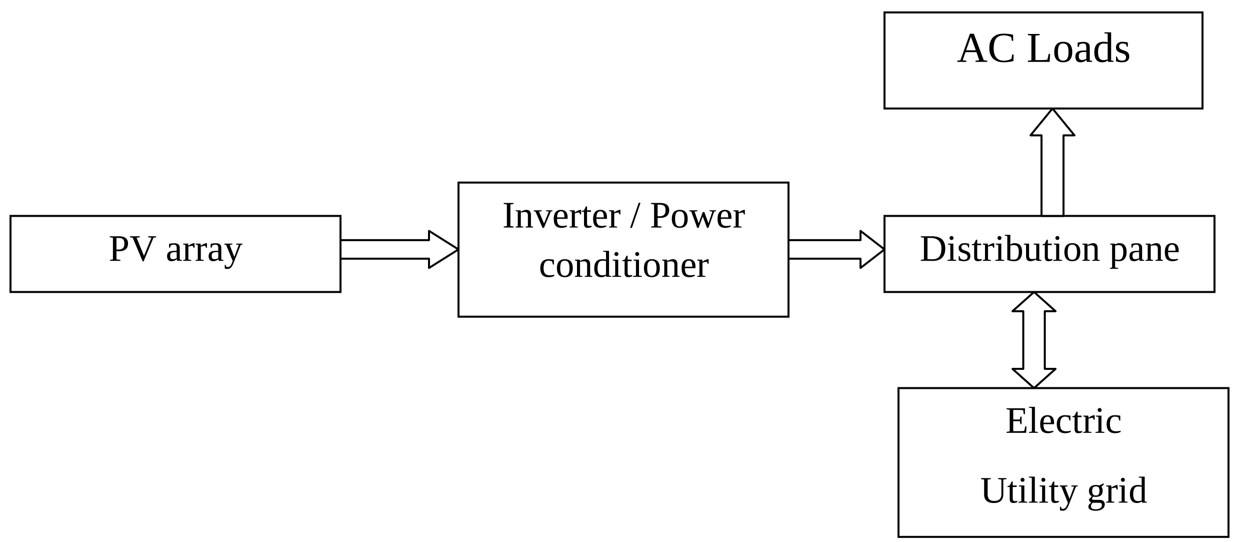


Figure 3.5: Schematic diagram of a grid connected PV system

Grid connected photo voltaic systems can be further divided as follows:-

- **Decentralized Grid connected PV system**

  Mainly used for small power range and rooftop installations.
- **Centralized Grid connected PV system**

  These systems have an installed power up to MW range and mainly used for medium and large grid connected photo voltaic system.

3.3 Solar PV modeling

PV cell is a semiconductor device which is mainly used to convert light energy into electrical energy. The output of solar PV cell that is solar energy not remains constant all the time, as it depends upon season, weather and day – night effect. The power extracted from photo voltaic system is function of voltage as well as current. The external conditions like temperature and solar irradiance affect the power output. The current-voltage (I-V) curve and the power – voltage (P- V) curve are non linear in nature even under presence of uniform solar irradiance and absence of partial shading.

Due to non linear characteristics of PV cell it is necessary to track a point which gives maximum power. As solar radiation increases, the current and power output of PV module increases. Other than that as cell temperature increases, voltage and power output of PV module decreases. Multiple maximum power points may exist on the PV curve due to effect of shading on some cells. Shading can occur due to clouds in the sky, nearby buildings and birds landing on panels. Due to complex nature of solar PV module it is advantageous to simulate a model under different illumination conditions.

A PV module generates very small power. The maximum power can be extracted under particular voltage condition due to non linear characteristics of PV cell. So the main task of a MPPT in a PV system is to continuously tune the system. It gives maximum power from the solar array and does not get affected by weather or load conditions.

A PV cell generates a voltage around 0.5 to 0.8 volts which further depend upon the semiconductor. Therefore, it is necessary to connect the PV cell either in series or in parallel to get higher output.

To design the PV system it is important that the modeling of PV module should be reliable and accurate. The modeling of solar PV cells can be done by below mentioned two methods:-

- Mathematical based modeling
- Electronic component based modeling

Mathematical based model of solar cell can be developed with the help of software, MATLAB. Mathematical based model is good to obtained desired output. It also considers the effect of solar irradiance, ambient temperature and load voltage.

3.4 Equivalent circuit of solar cell

The operation of the p-n junction solar PV cell can be explained by diode equation. The p-n junction is fabricated over a layer of semiconductor. The illumination comes from sun light is nothing but the photons. Solar cell absorbed these photons only when its energy is greater than semiconductor band gap energy. When valence electrons lose their existence from the atoms then, the generation of electron hole pair takes place. Due to the internal electric fields of the p-n junction current starts to flow in the circuit.

3.4.1 Solar cell model

IDEAL MODEL: - Ideal solar cell consists of a current source and a diode which are connected in series. The photon current which is produced by current source is directly proportional to the solar irradiance G. Short circuit current and open circuit voltage are two key parameters which are used to characterize photo voltaic cell. The value of short circuit current and open circuit voltage is provided by the data sheet.

The simplified circuit of solar cell without considering losses is shown in figure 3.6.

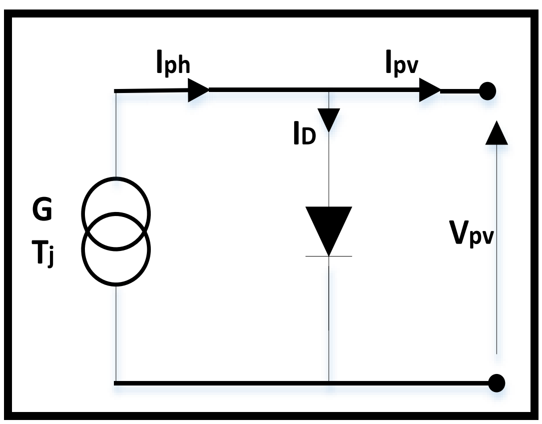


Figure 3.1: Simplified equivalent circuit of ideal solar cell

From Kirchhoff's law, we have-

$$I_{pv} = I_p - I_d \tag{3.1}$$

Where

$$I_d = I_O \left[e^{\frac{q(V_{pv})}{AKT_j}} - 1 \right] \quad (3.2)$$

Thus

$$I_{pv} = I_p - I_O \left[e^{\frac{q(V_{pv})}{AKT_j}} - 1 \right] \quad (3.3)$$

Where,

I_{pv} is the current through PV cell.

V_{pv} is the voltage across PV cell

I_p is the photon current that is equal to short circuit current

I_o is the reverse saturation current of diode

q is electron charge ($1.6*10^{-9}$ C)

K is boltzman constant ($1.381 * 10^{-23}$ J/K)

I_d is current shunted through the intrinsic diode

A is diode intrinsic factor

T_j is junction temperature of panels (Kelvin)

3.4.2 Solar cell model with ohmic losses

Practical Model: - Figure 3.6 shows the practical circuit for PV cell. This circuit consists of photo current source, a diode, a series resistor and a parallel resistor. This model takes account of ohmic losses and the material resistivity due to levels of contact.

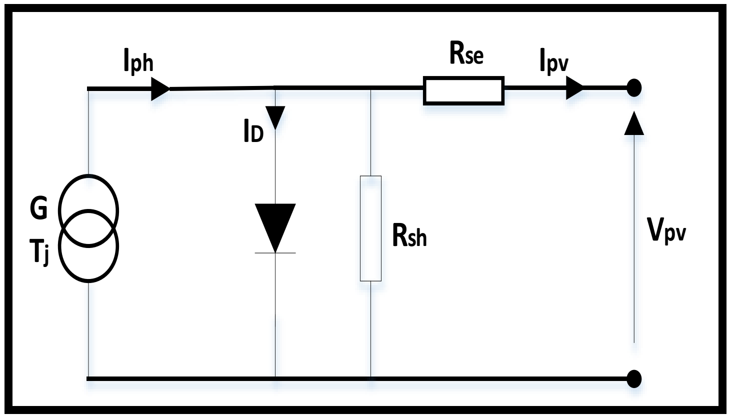


Figure 3.7: Simplified equivalent circuit of practical solar cell [51]

The PV cell output current can be defined as a function of the output voltage of the PV cell as follows:-

$$I_{pv} = I_p - I_o\left[\left[e^{\frac{q(V_{pv}-R_S I_{pv})}{AKT_j}} - 1\right] - \frac{(V_{pv} + R_s I_{pv})}{R_{sh}}\right] \quad (3.4)$$

Where,

R_s is parasitic series resistance

R_{sh} is parasitic shunt conductance

The photon current I_p is proportional to the sun irradiance and to the cell temperature, which is given by,

$$I_p = I_{sc}\left[1 - \alpha(T - T_{ref})\right]\frac{G}{G_o} \quad (3.5)$$

Where, $\alpha = 0.0012 * I_{sc}$, which is the temperature coefficient of short circuit current

G is solar irradiance level (kW/m^2)

G_o is solar irradiance under normal operating conditions, 1000 kW/m^2

3.5 Conclusion

In this chapter various application of PV system has been discussed like in standalone and grid connected system as well as PV modeling has been explained with theoretical and practical methods.

Chapter 4

POWER CONDITIONING DEVICES OF PHOTO VOLTAIC SYSTEM

A photo voltaic system is the combination of solar panels and power conditioning devices. The branch of power electronics which is called power conditioning is very important from view point of management of electrical energy. It helps to draw maximum power from solar panels and also provides a high quality AC output.

To manage electrical power in PV system it is necessary to find modern and sophisticated methods. In absence of power conditioning devices power generated by solar panels will be wastefully dissipated as heat in the system components.

To enhance the efficiency of PV system electronics play very vital role. Along with that to increase the solar generated electricity appropriate electrical techniques can be implemented for grid connected PV system.

It is necessary to maximize the energy efficiency as solar energy systems are more expensive in compare to other energy sources. Power conditioning devices are also used for energy storage.

Some power conditioning devices which are used to increase the efficiency of PV system are as follows:-

1. DC/DC converters
2. Maximum power point trackers
3. Inverters

4.1 DC/DC converters

DC/DC converters used in number of circuits for example battery chargers and maximum power point trackers. With the help of DC/DC converter, the output voltage and current of solar panel can be adjusted to any value. In modern power electronics DC/DC converters are more preferable than linear power regulator [47].

Linear regulators provide high quality DC voltage but it energy efficiency is poor. Linear regulator keeps constant output voltage and functions as a variable voltage divider. It is highly inefficient circuit as it dissipates heat in the resistive elements.

Maximum power efficiency is a main goal in solar PV system that's why DC/DC converters are preferred. Linear regulators provide an output voltage, less than input. Whereas DC/DC converters are flexible as they can step up as well as step down the input voltage.

DC/DC converters must be able to maintain controllable or constant output voltage. By proper switching topology the above goal can be achieved despite variations in the input voltage. The operations of switches must be controllable and periodic to achieve a stable average output voltage. In DC/DC converters mainly two energy storage elements are used that is inductor and capacitor. Other than that transistor is always used as a switching element and with the help of control circuit proper and periodic switching of transistor can be achieved. Transistors types which are mainly used for switching are BJT (bipolar junction transistor) and FET (Field effect transistor).

MOSFET is best suited for switching circuit as it dissipates very little power in on and off states and with the help of this switching circuit can achieve high power efficiency. In the ON state, due to low resistance very small voltage drop will takes place across switching device whereas in the OFF state very little current will flow that is nothing just the leakage current.

It is advantageous to operate switching regulators at high frequencies. High frequency of switching device decides the size of other components which further decides the cost. Due to high frequency of switching regulators, components used such as capacitor, inductor and transformer can be of smaller size.

Output voltage of PV system, power transfer and battery charging can be optimized with the help of DC/DC converter. DC/DC converter converts constant output voltage and current of solar panel into variable one. This conversion can takes place in between various places. For example:-

- Between a battery and inverter
- Between a solar panel and an inverter
- Between a battery and an inverter

It is usually seen at the output of solar panels and its ability is used for maximum power point trackers.

For safety benefits, transformers can be used along with DC/DC converter, as transformer provides electrical isolation. Transformer is generally used at the input side of DC/DC converter in series with switching element.

4.1.1 DC analysis of PWM boost converter

The circuit of boost converter is shown in figure 4.1.For steady state operation its output voltage V_o is always higher than input voltage V_i. This converter circuit boosts the output of solar panel to higher level. It consists of a power MOSFET, a diode D_1, an inductor L , filter capacitor C and a load resistor R_L. The switch is turned ON and OFF at switching frequency with the ON duty ratio.

The switching frequency is given by,

$$f = \frac{1}{T} \tag{4.1}$$

And the ON duty ratio is given by,

$$D = \frac{t_{on}}{T} \tag{4.2}$$

Where t_{ON} is the time interval when the switch S is remains on.

The boost converter can operate in two modes which depend upon the waveform of inductor current. The two modes are as follows:-

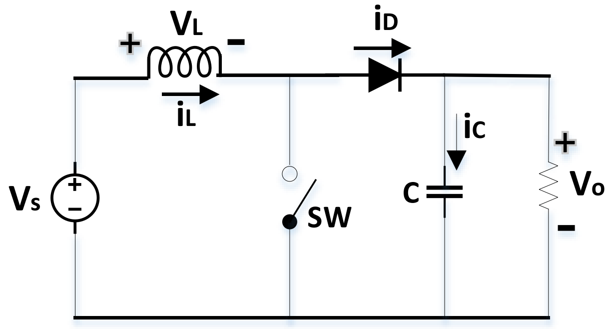
- Continuous conduction mode
- Discontinuous conduction mode

Continuous conduction mode is considered for the project. Figure 4.2 shows the equivalent circuit of boost converter for continuous conduction mode when the switch is ON and diode remains reverse biased. Whereas figure 4.3 depicts when the switch S is OFF and diode is forward biased.

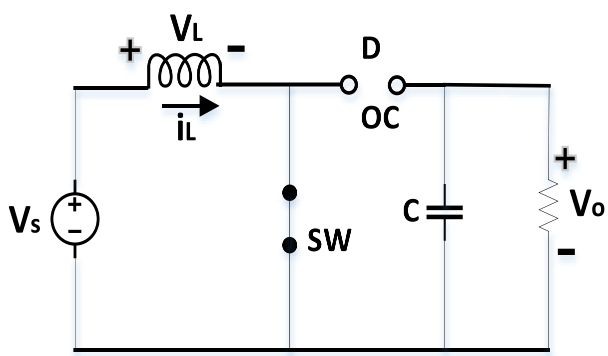
Assumptions for analysis of boost converter:-

1. The switch is closed for DT time and it will remain open for (1-D)T.

2. All components are ideal.
3. The value of the capacitor is high and output voltage remains constant.
4. The inductor current always remains positive.



(a)



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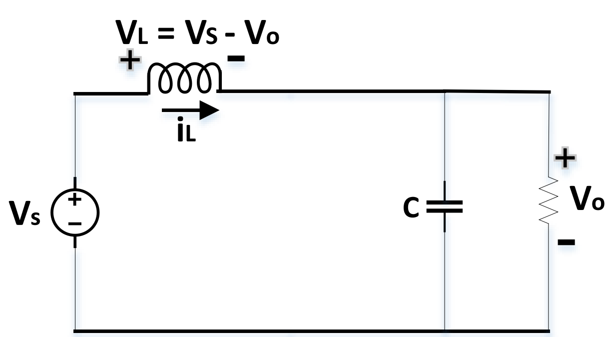


(c)

Figure 4.1: Boost converter (a) Main circuit (b) Equivalent circuit for switch closed (c) Equivalent circuit for switch open [48]

Analysis for the switch closed:-

When the switch is ON, the diode will remain open circuit. The current will flow through inductor and voltage source. The voltage across inductor is given by,

$$V_L = V_S = L\frac{dI_L}{dt} \tag{4.3}$$

Or

$$\frac{dI_L}{dt} = \frac{V_S}{L}$$

When the switch is closed the current increases linearly as the rate of change of current is constant. Change in inductor current for switch closed is given by-

$$(\Delta i_L)_{Closed} = \frac{V_S DT}{L} \tag{4.4}$$

Analysis for the switch open:- [48]

When the switch is open, the diode become forward biased as the inductor current cannot decrease instantaneously and it provides path for inductor current.

$$V_L = V_S - V_O = L\frac{dI_L}{dt}$$

Or

$$\frac{dI_L}{dt} = \frac{V_S - V_O}{L} \tag{4.5}$$

When the switch is open the current increases linearly as the rate of change of current is constant. Change in inductor current for switch open is given by-

$$(\Delta i_L)_{Open} = \frac{(V_S - V_O)(1-D)T}{L} \tag{4.6}$$

For steady state operation, the net change in inductor current will remain zero and it is given by,

$$(\Delta I_L)_{Closed} + (\Delta I_L)_{open} = 0$$

By solving equation 4.4 and 4.6,

$$V_O = \frac{V_S}{1-D} \tag{4.7}$$

By the above equation it can be concluded that boost converter produces an output voltage which is always greater than or equal to input voltage.

For design perspective values of inductor and capacitor is very important. It can be calculated by the formula given below:-

$$L = \frac{V_S DT}{\Delta i_L} = \frac{V_S D}{\Delta i_L f} \tag{4.8}$$

$$C = \frac{D}{R\left(\frac{\Delta V_O}{V_O}\right) f} \tag{4.9}$$

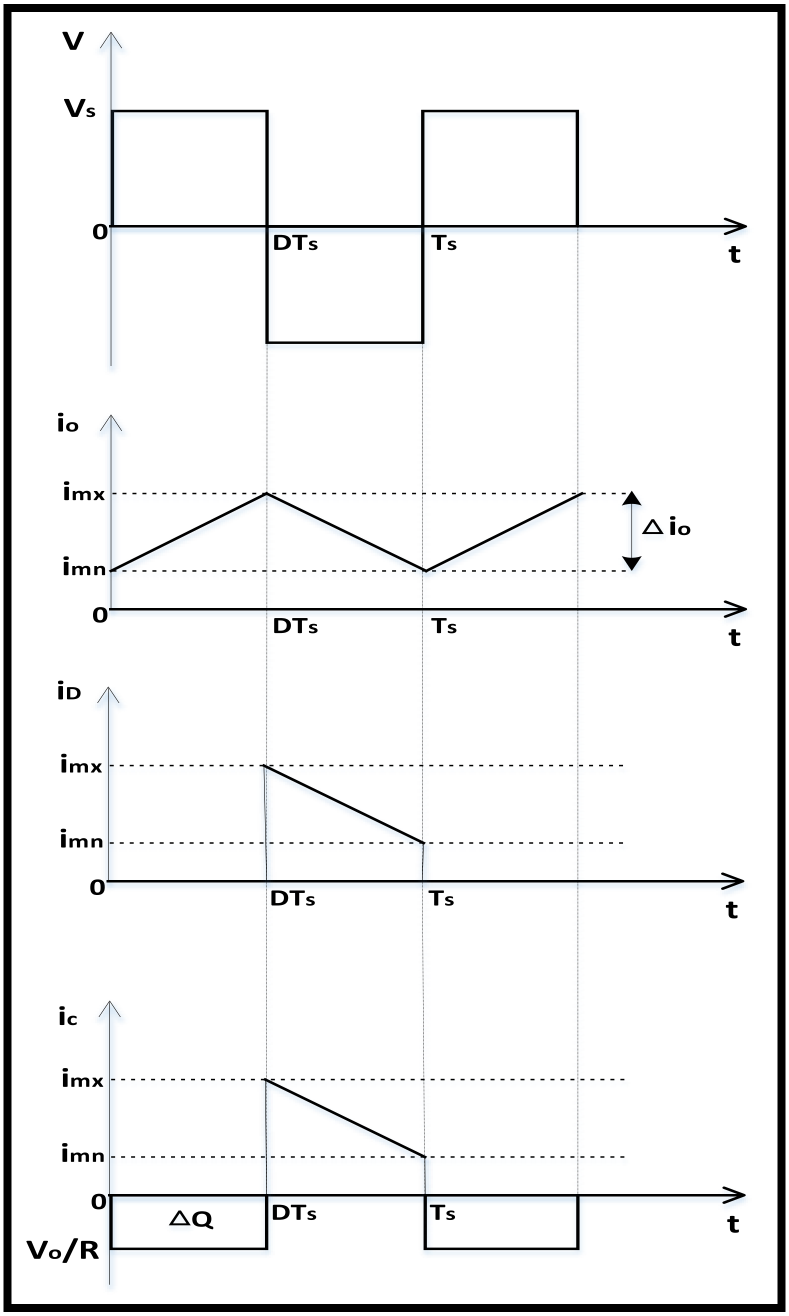


Figure 4.2 : Boost converter waveform (a) Inductor voltage (b) Inductor current (c) diode current (d) capacitor current

Hence, DC/DC converter plays an important role for grid connected photo voltaic system. It also reduces the requirement of transformers in the circuit which further reduces the cost, losses and complexity in the circuit.

4.2 Maximum Power point trackers

The characteristics of PV cell is non linear in nature hence, under particular voltage condition only maximum power can be extracted. In photo voltaic array maximum power point tracking algorithm is used to get maximum output power. Perturb & observe and incremental conductance are some direct control techniques which have less complexity and easy to implement.

The output of PV module is generally low so, MPPT continuously tune the system to draw maximum power from PV array as well as it does not get affected by the weather condition and load variation.

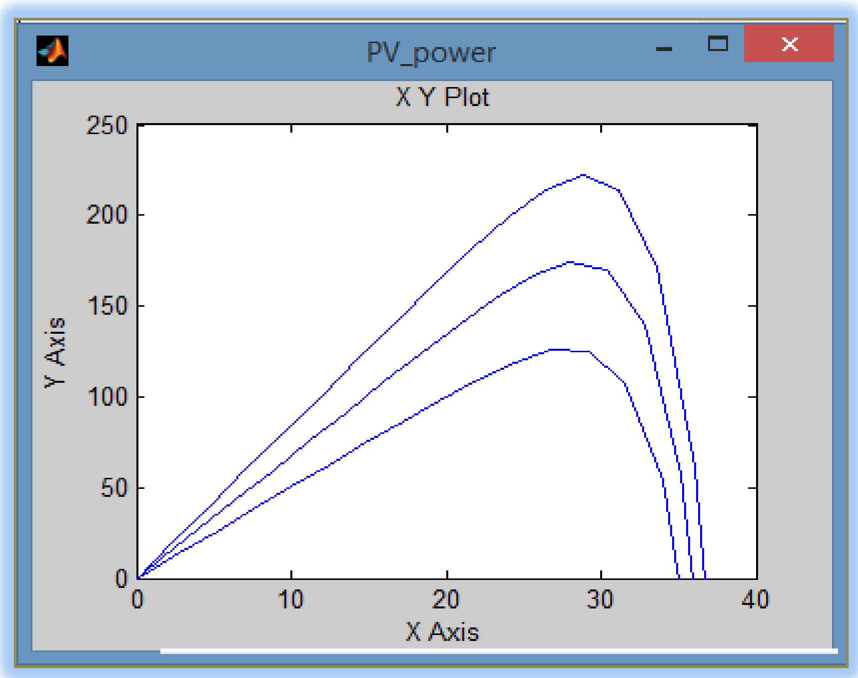
MPPT play very important role to improve the efficiency of solar panel. According to maximum power point theorem by adjusting load impedance equal to source impedance output power can be maximized. To get maximum output voltage MPPT helps to find the duty cycle. If output voltage increases then output power also increases.

Due to the variation in temperature and illumination level of solar cell, the maximum power point can vary frequently. So, to avoid the above condition a dynamic system inserted between solar panel and the load [49]. That system is known as maximum power point tracker.

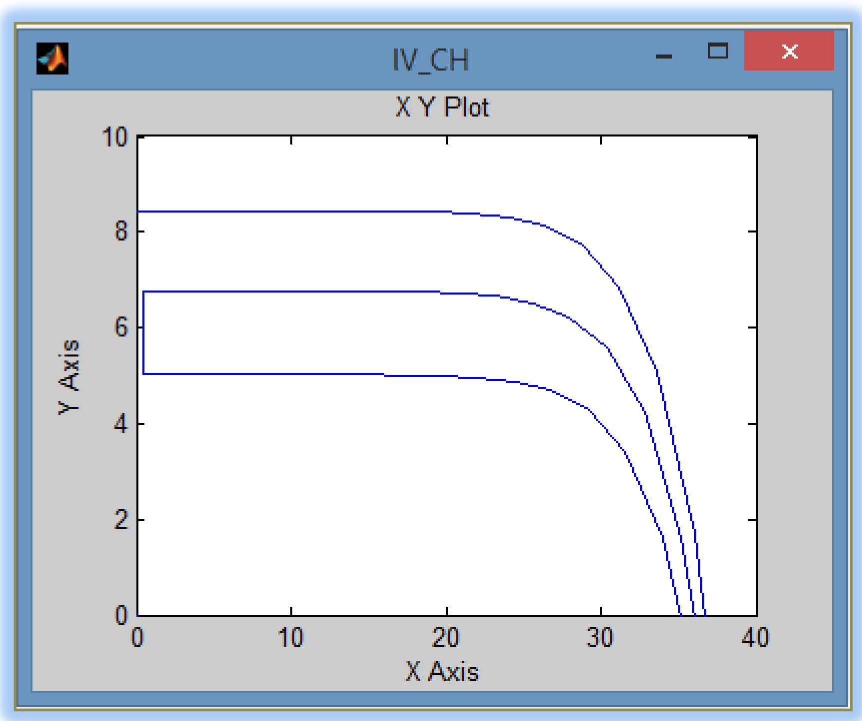
MPPT is used to vary the duty ratio of the DC –DC converter and also vary the current and voltage at its input which can be finding out by voltage and current sensors. It is considered that power efficiency of DC-DC converter is very high that means all the power present in input is transferred to load without much variation [50].

To find maximum power point MPPT uses an iterative process. In this type of operation to calculate the power at its input, in this type of operation variation of duty ratio takes place in one direction. Due to the variation if the increase in power occurs then it results into further increment of duty ratio in the same direction. Apart from that the duty ratio is adjusted in reverse direction, if the power at the input deceases [50].

Figure 4.3 shows the I-V and P-V characteristics of PV cell. These graphs show that at irradiation or illumination increases the graph shifted upwards. The top one is at irradiation 1200 kW/m^2 , middle one at 1000 kW/m^2 and last one at 800 kW/m^2 .



(a)



(b)

Figure 4. 1: (a) PV (b) IV characteristics under different irradiance

The maximum power point is located at knee of the I-V curve and it is indicated at voltage MPP and current MPP. Power delivered to the load changes only when if there are any changes in current and voltage supplied from PV array.

4.2.2 MPPT operation

As mentioned earlier, MPPT is nothing just a DC/DC converter which is used to vary duty ratio in order to get maximum power output at load. This is due to the fact that any change in duty ratio will further change the current drawn from MPPT and this leads to do changes in operation on I-V curve of MPPT. The current which is drawn by the MPPT is proportion to duty ratio (t_{on} / T).

The number of voltage and current sensors depending upon the configuration can be employed in a PWM feedback loop to find the power present at the input of MPPT and the input of MPPT is nothing but the PV current and PV voltage. To maximize the power at input, PWM control loop vary the duty ratio. A block diagram of MPPT is shown in figure 4.4.

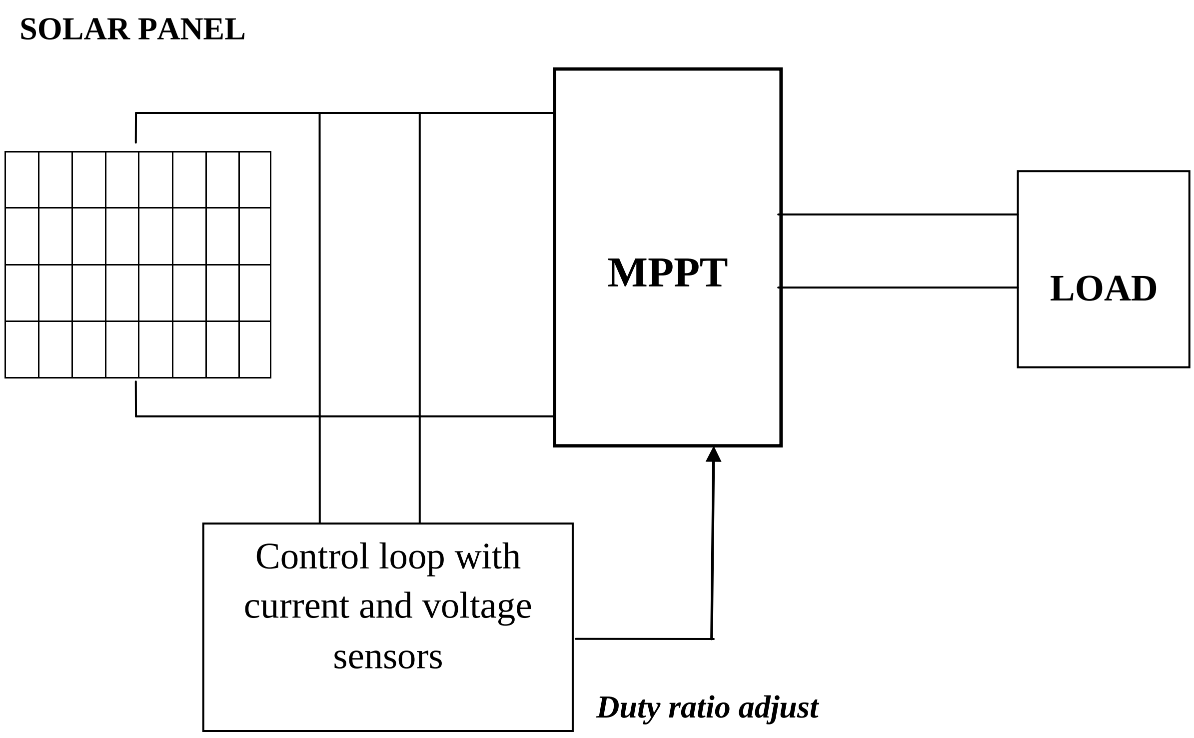


Figure 4.4:MPPT with PWM control loop

There are number of ways to control MPPT for example P & O and incremental conductance. The voltage and current sensors which are part of PWM feedback loop take care of power at the input of MPPT that whether it is increased or decreased. If there is an increase in power the MPPT will either increases or decreases the duty ratio in same direction. Once a decrease in power occurs, the system will set the duty ratio in opposite direction.

P&O is direct control method which is less complex and easy to implement but it has some drawbacks that is slow response and it gives transient nearby MPPT.

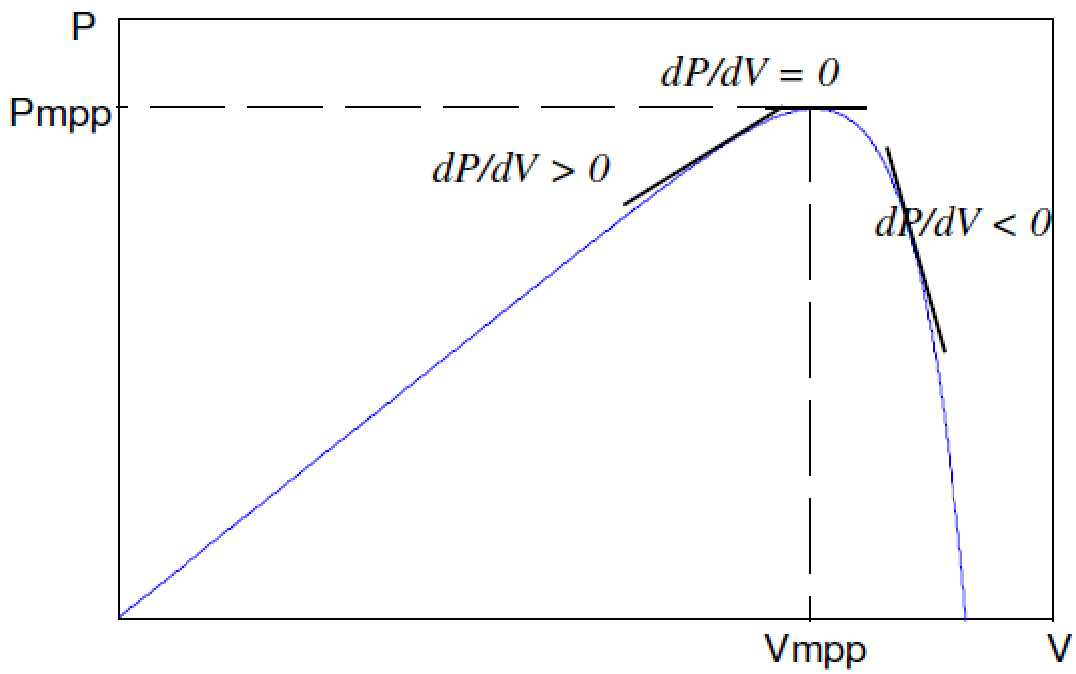


Figure 4.5: Change in power with respect to voltage at different positions [58]

Another method for MPPT is incremental conductance method. This method is based on the fact that at the MPP slope of the PV panel power curve is zero. According to d(VI)/dv = 0, the result is,

$$\frac{\Delta I}{\Delta V} = \frac{-I}{V}, \text{ At Maximum power point}$$

$$\frac{\Delta I}{\Delta V} > \frac{-I}{V}, \text{ At left of Maximum power point}$$

$$\frac{\Delta I}{\Delta V} < \frac{-I}{V}, \text{ At right of Maximum power point}$$

The working of incremental conductance method is explained by a flowchart which is shown in figure 4.6.

The PV panel should operate at particular voltage which is given by V_r . The speed of MPP tracking can be finding out by increment size. Fast tracking can be achieved with bigger increments. There is a possibility that system can oscillate around MPP.

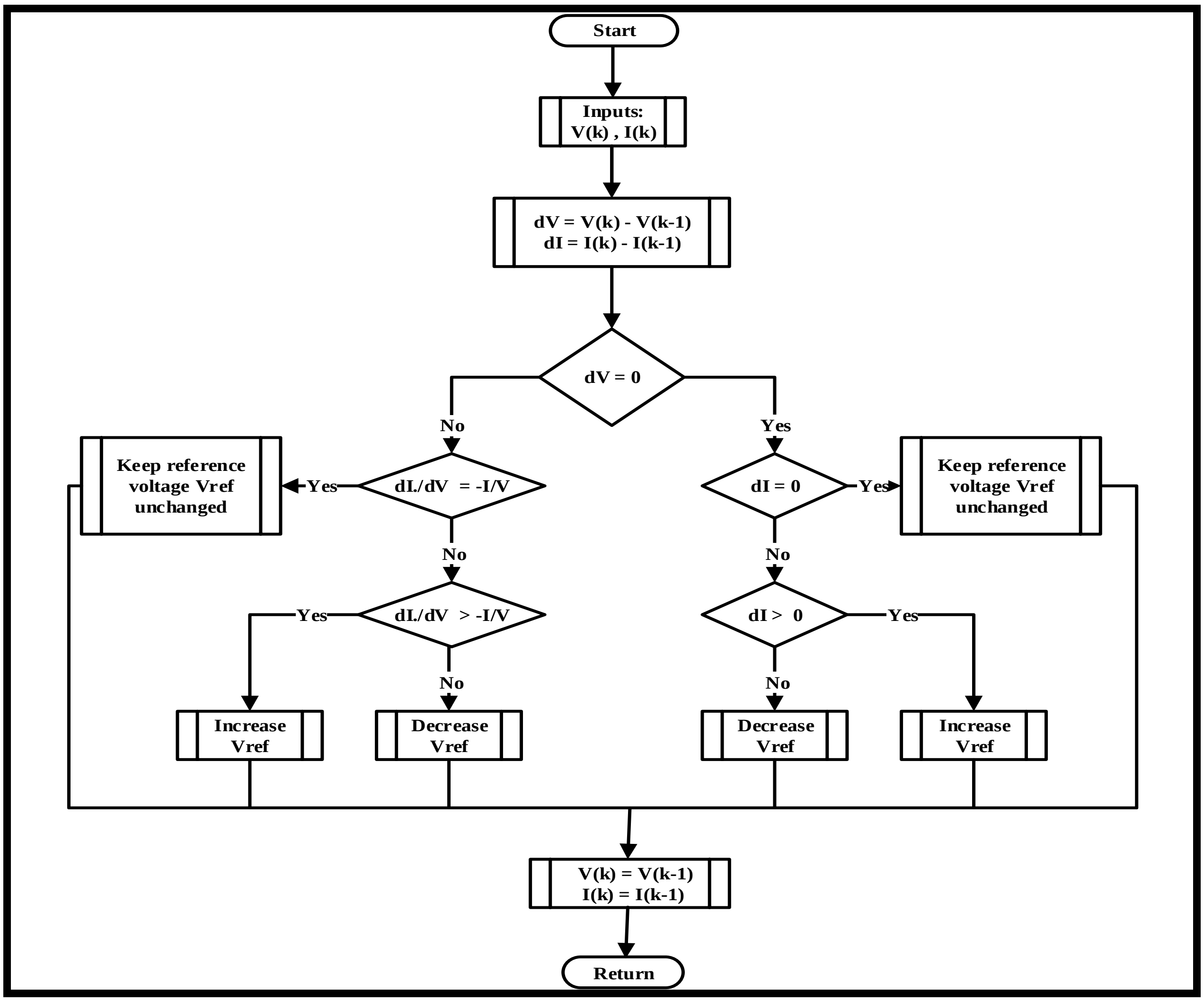


Figure 4.6 Flowchart of incremental conductance method

For grid connected system MPPT is best alternative but it can be used for standalone system in conjunction with battery chargers. Some power loss can take place in DC/DC converter but MPPT enhance the system efficiency [58].

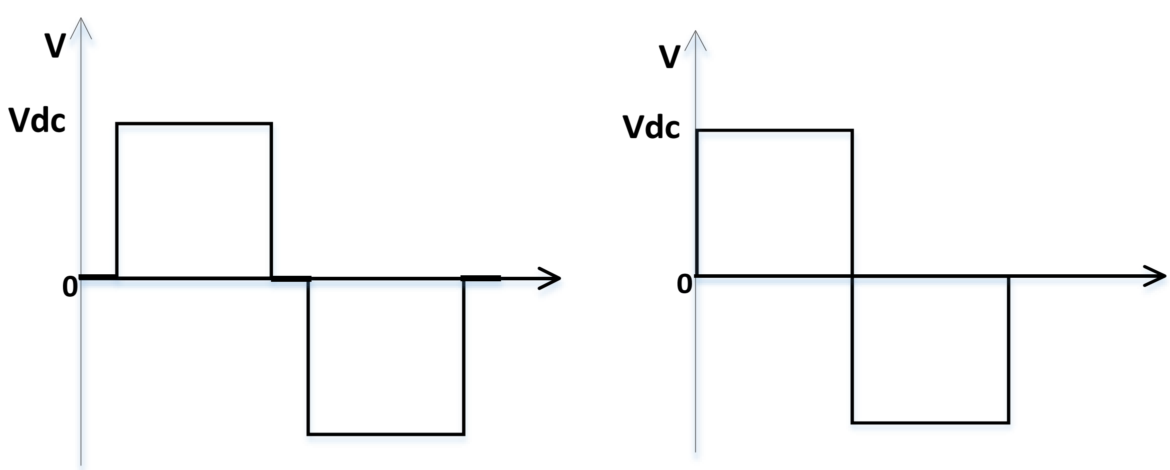
4.3 PV Inverters

There are number of inverter topologies which can be classified on the basis of their output waveform. These topologies are:-

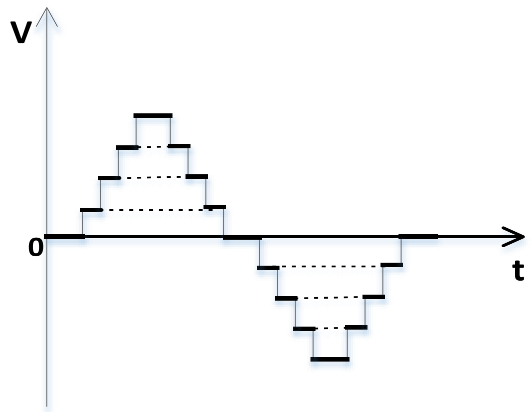
- Square wave Inverter
- Quasi square wave Inverter
- Multilevel Inverter
- High frequency sine wave Inverter

Square and quasi square wave inverters are not at all recommendable due to its poor quality waveform. Apart from that multilevel inverter and sine wave inverter are considered in most of the applications. The output of these inverters varies due to its switching frequency.

Multilevel inverter gives good quality waveform. Its switching frequency is low and its output is staircase in nature. This method is quit efficient and robust. Sine wave inverter works on high switching frequency that's why its output is pure sinusoidal. These inverters are compact and its cost is low. Waveforms of different inverter topologies are shown in figure 4.7.



(a) (b)



(c)

Figure 4.7 Inverter topologies by waveform

(a) Quasi Square wave inverter (b) square wave inverter(c) multilevel inverter

4.3.1 Conventional inverters (VSI and CSI)

To get single stage DC/AC conversion Current source inverter (CSI) and voltage source inverter (VSI) are mainly used. VSI and CSI have some shortcomings like large voltage variation that's why it's not preferable for photo voltaic system.

VSI is a step down inverter, hence to avoid over modulation it is preferred that DC link voltage should be higher than the peak line to line grid voltage. The CSI is a step up inverter. So in this also to avoid over modulation, the dc link voltage should be 0.866 of the peak line to line grid voltage.

For VSI, if line to line supply voltage is 415 V_{rms} , then the DC link voltage i.e. the output of DC/DC converter around the maximum power point should be 587 volt. In contrast, for CSI at no load the DC link voltage should be less than 508 volt. As compare to VSI, CSI require less modulation depth. The main reason behind this is that at full power its operation takes place at higher current [52].

4.3.1.1 Standard Voltage source inverter

In VSI the inverter is fed from the DC voltage source or PV source and to get smooth DC link voltage large capacitor is connected in parallel to it. An inductive filter is used in source side or AC side to absorb the rapid change in voltage and to reduce the ripples in current waveform [52].

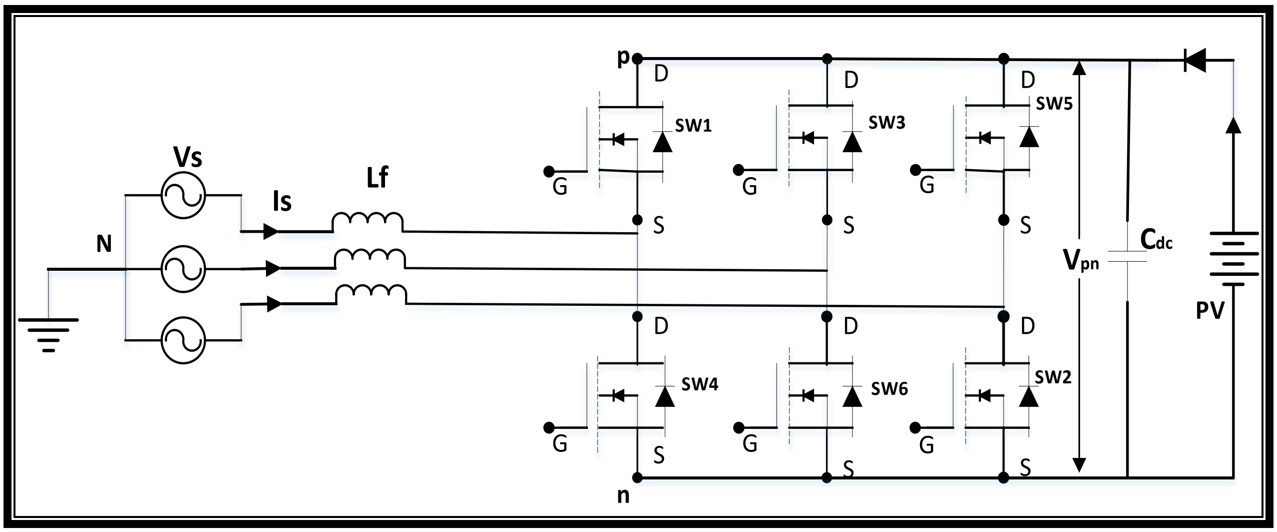


Figure 4.8 Voltage source inverter

4.3.1.2 Standard current source inverter

In CSI large DC link inductor is connected in series with the DC voltage source. On source side or AC side capacitor filter is used to absorb the change in current as well as to smooth the grid ripple voltage [52]. Due to switching current ripples generated at AC side hence, AC inductors are used to overcome this problem.

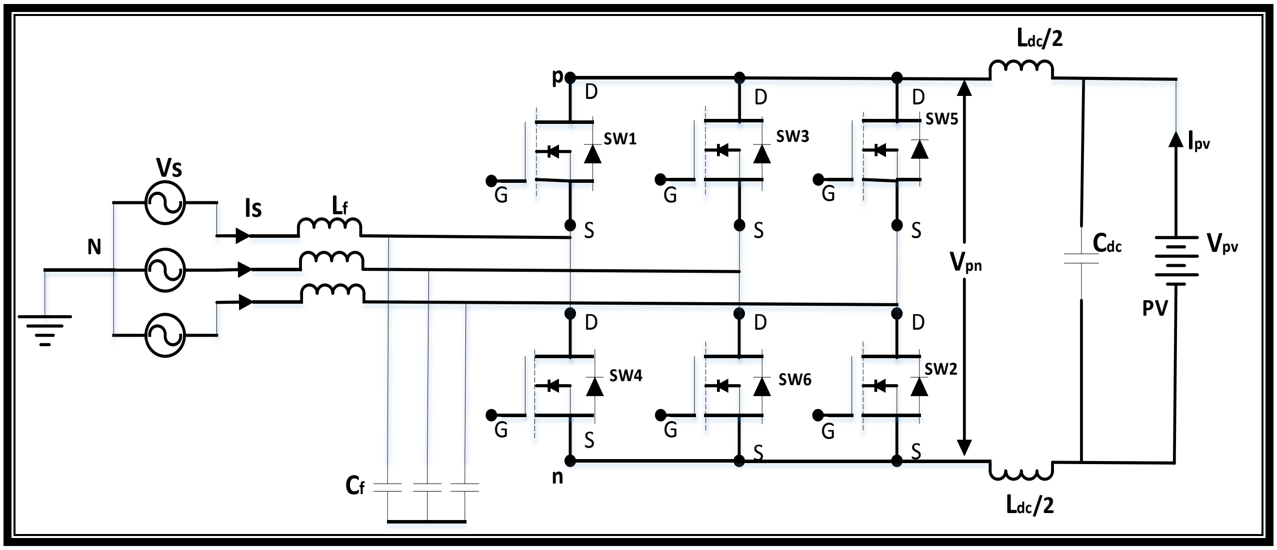


Figure 4.9 Current source inverter

4.3.2 Multilevel converters

The main concept of multilevel inverter is to achieve high power. In multilevel inverter to get staircase output voltage waveform, several lower voltage DC sources are connected in series with power semiconductor devices. To generate DC voltage renewable energy source, batteries and capacitors can be used. By proper commutation of semiconductor switches, it is possible to achieve high voltage with less T.H.D. at output. Mainly one or more DC sources are used in most dominant multilevel inverters [53].

For high power applications multilevel inverter is the best choice. Multilevel inverters are not that much appealing as high frequency sine wave inverters. Low frequency inverters have efficiency and robustness but the high frequency inverters are compact and less expensive.

Figure 4.10 represents the comparison of two level converter and multilevel power converters.

The maximum power limit of three phase converter depends upon the maximum voltage and current of a switching component. There is an inverse relation between powers and switching frequency that means it the power of the switch is high then the switching frequency will be low.

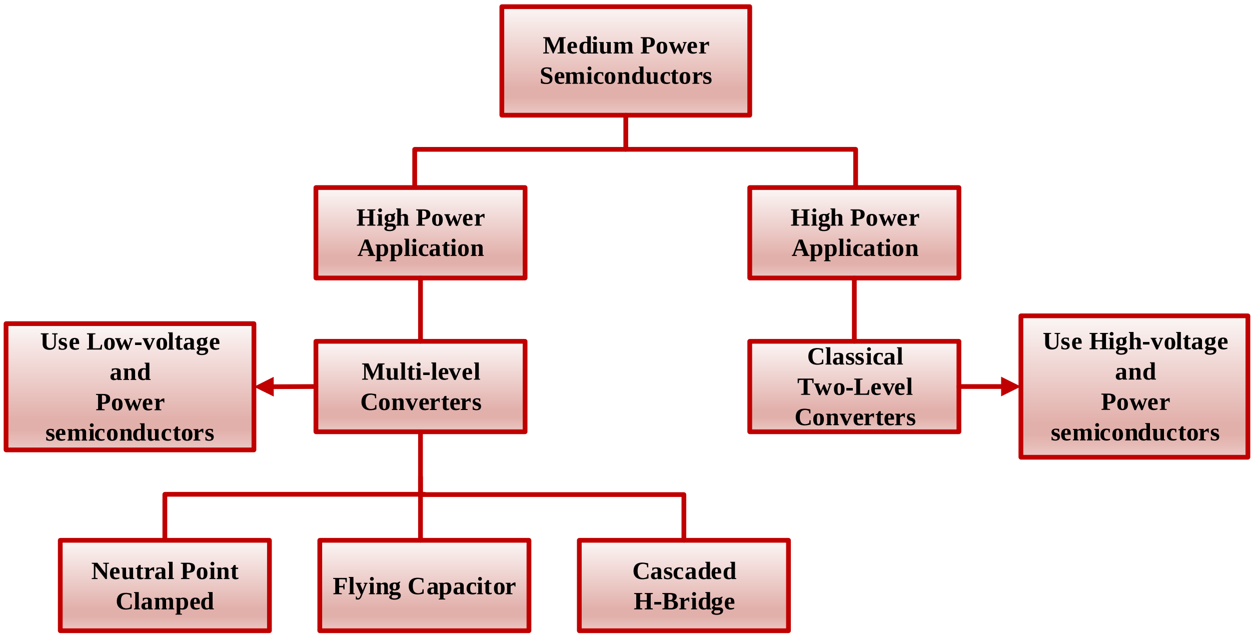


Figure 4.10 Classification of converter

To overcome the above problem switches can be connected in parallel or in series. But there is a problem in series connection as in this case it is difficult to synchronize the commutation of switches.

In series connection if one of the switches will turn off then entire voltage of circuit will come across remaining switches so there is a chance of blow up of switches. Instead parallel connection is less complicated due to the positive coefficient property of MOSFETs and IGBTs.

Advantages of multilevel converters

- Due to greater number of levels of output voltage power quality of waveform increases and its total harmonic distortion decreases. So, filter size can be reduced at AC side which further decreases the losses as well as cost.
- Generate better output waveforms with lower dv/dt.
- These converters do not require transformers and can be directly connected to high voltage source, which reduces the complexity and cost.

Disadvantages of multilevel converters

- Increases complexity in the circuit as it requires large number of semiconductor switches.
- To create the DC voltage step capacitor banks are required.

The most common multilevel inverter topologies are [53]:-

- Diode clamped(neutral point clamped)
- Flying capacitor (Capacitor clamped)
- Cascaded H – Bridge

All types of multilevel inverters can produce same output voltage but main difference occurs due to control complexity, average voltage/current, number of switches and their topology.

Among these three different topologies, Cascaded H Bridge multilevel inverter is used in this project due to its several advantages.

4.3.2.1 Cascaded H Bridge multilevel inverter

Cascaded H bridge multilevel inverter mainly used in medium and high power applications. This method use independent DC sources and each connected with individual bridge. A circuit with 2 DC voltage source is shown in figure 4.11 [55].

The output of each H bridge is given by 0,+V_{dc}, -V_{dc} . The combination of individual bridge voltage gives the total instantaneous output voltage. Thus for five level inverter the output v_o is given by +2 V_{dc} , +V_{dc} , 0, - V_{dc} , -2 V_{dc}.

Each H Bridge operates with different switching scheme and this is used to control harmonics as well as amplitude.

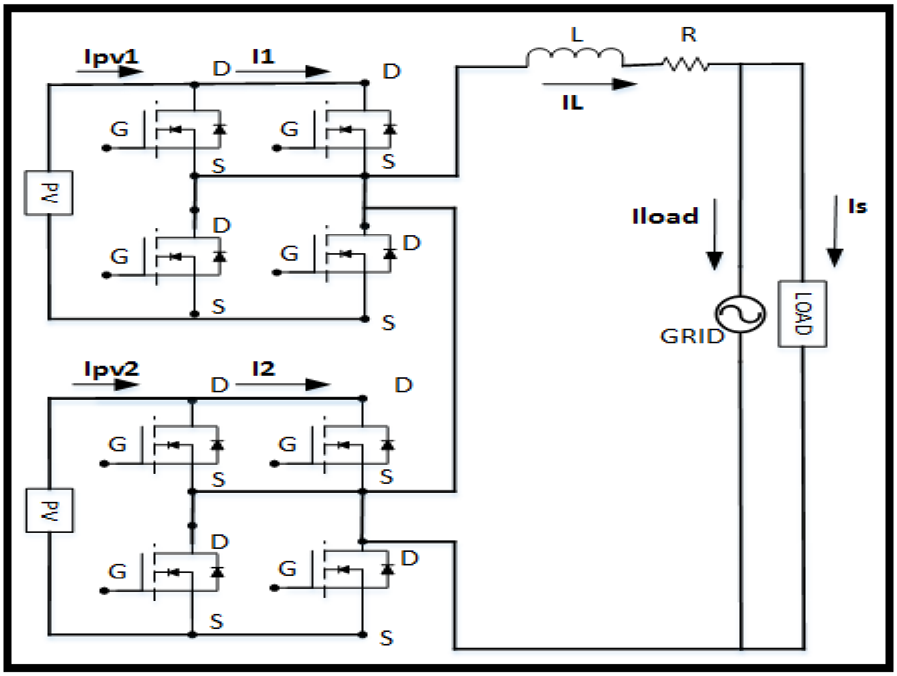


Figure 4.11 Single phase five level H Bridge multilevel inverter

Characteristics of Multilevel inverter

- The number of separate DC sources attached to each bridge decides the number of output levels of multilevel inverter.
- The relation is m= 2p+1, here p is the number of DC sources and m is the output levels of multilevel inverter.
- No even harmonics present.
- It gives staircase output or which is quarter symmetric in nature. The above condition is necessary to generate sine like wave.
- In this topology power can be easily scaled as it consists of series of power conversion cells.

4.3.2.1.1 Control techniques for CHMLI

Control techniques for the CHMLI can be classifies into the three main categories:-

1. Selective harmonic elimination technique (SHE)

2. Pulse width modulation technique (PWM)
3. Optimized harmonic stepped waveform technique (OHSW)

Among all control techniques, in project the main focus is given to PWM techniques.

Pulse width modulation technique (PWM)

To control the AC output of inverter the best known technique is PWM. To achieve the low frequency output this technique varies the duty cycle of the switches at a higher frequency. Some unwanted harmonic components present in the train of pulses and it should be minimized in order to get desired output voltage and current.

The PWM technique can further classify as follows [54]:-

(a) Open loop control techniques
    i. Sinusoidal PWM techniques
    ii. Space vector PWM techniques
    iii. Sigma delta PWM techniques
(b) Closed loop control techniques
    i. Hysteresis current controller technique
    ii. Linear current controller technique
    iii. Dead band current controller technique
    iv. Optimized current controller technique

Among all above discussed categories SPWM is one of the best and easy techniques to control the CHBMLI on FPGA.

4.4 Classification of SPWM technique

The classification of SPWM technique is based upon carrier signal and modulating signal as shown in figure 4.12.

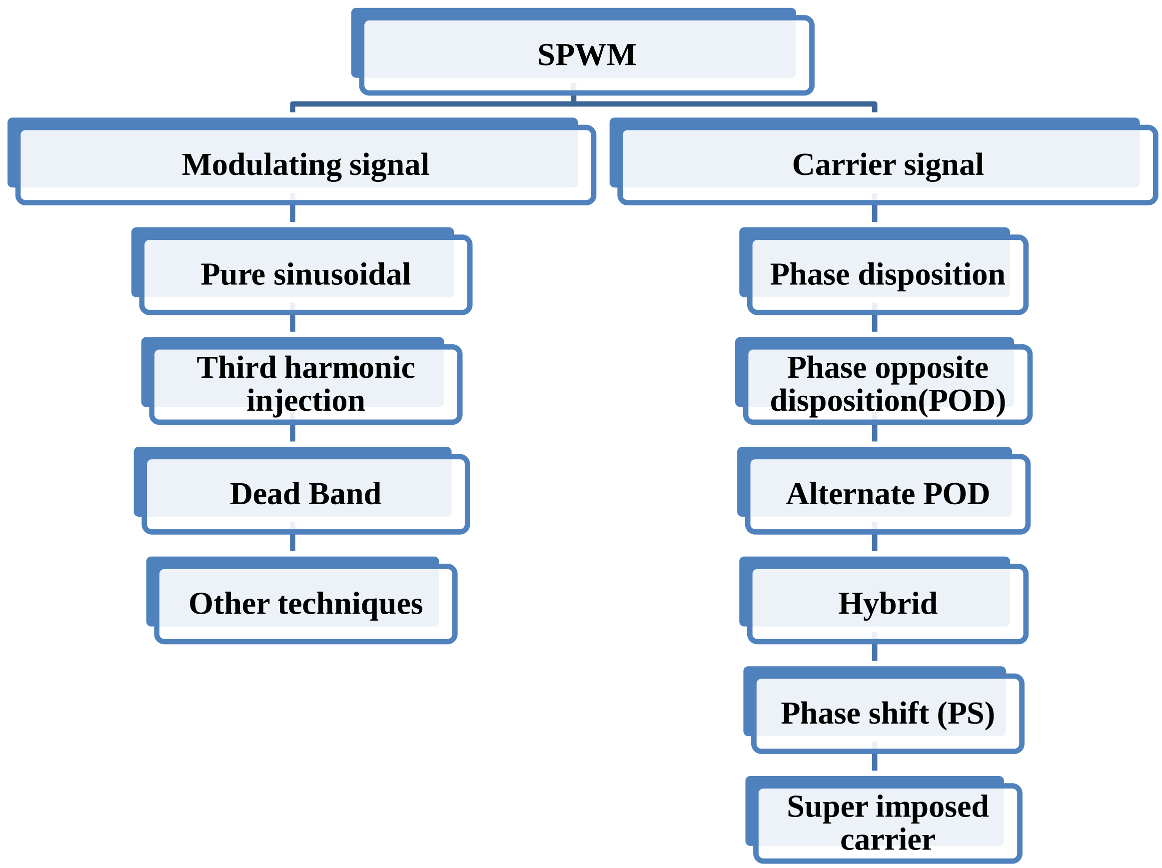


Figure 4.12 Classification of SPWM technique

Hence there are number of techniques which can be used to generate staircase output. In this project Phase disposition technique is considered.

Advantages of CHBMLI

- This topology does not require diode or capacitors for clamping,
- This inverter gives the output waveform which is quite near to sinusoidal and even filters are not required.
- Cost effective
- High efficiency

Disadvantages of CHBMLI

- Need separate DC source with each leg
- NO common DC bus

Application of CHBMLI

- Motor drives
- Active filters
- Electric vehicle drives
- DC power source utilization
- Power factor compensators
- Back to back frequency link systems
- Interfacing with renewable energy resources

4.5 Conclusion

In this chapter all power conditioning devices are discussed. In this chapter many MPPT algorithms are discussed and mainly incremental conductance is reviewed. Other than that type of multilevel inverters and mainly the significance of CHBMLI is discussed.

Chapter 5

SINGLE-PHASE CASCADED H-BRIDGE MULTILEVEL INVERTER FOR GRID CONNECTED PHOTOVOLTAIC SYSTEMS [56]

In case of cascaded H Bridge MLI an individual DC source is required for each H Bridge and this combination gives high voltage as well as high power. Due to this feature we can use this method in large grid connected photovoltaic system [57]. Along with this individual and independent control can be achieved by applying separate DC source to each inverter. Henceforth MPPT i.e. Maximum power point tracking is possible and with the help of this we can get the maximum energy from the combination of PV panels. The low cost, reliability, robustness, efficiency and modularity of multilevel inverter attract the people toward this.

The multilevel inverter topology for the Photovoltaic system is discussed in this chapter. To avoid the panel mismatches issue individual MPPT control is required. To achieve the above mention phenomenon as well as for reactive power control one control scheme is proposed in this chapter.

5.1 Topology Description

The structure of cascaded multilevel inverter consists of N H-bridge inverter converters which are connected in series. Each inverter consists of DC link voltage to generate modulated output voltage. Each DC link is fed by a short string of PV panels. The sum of each individual output voltage is used to find total output voltage. With the help of different combinations of the switches, each inverter is able to produce three output voltages that are 0, $+V_{dc}$ and - V_{dc}. The number of voltage levels of the phase voltage is given by,

$$\mathbf{M_{ph} = 2N+1}$$

Where N is the number of inverters

Due to this high quality and (2N+1) levels output voltage waveform, harmonic reduces in the generated current as well as reduces the size of output filter. It also reduces the voltage stress on the semiconductor switches.

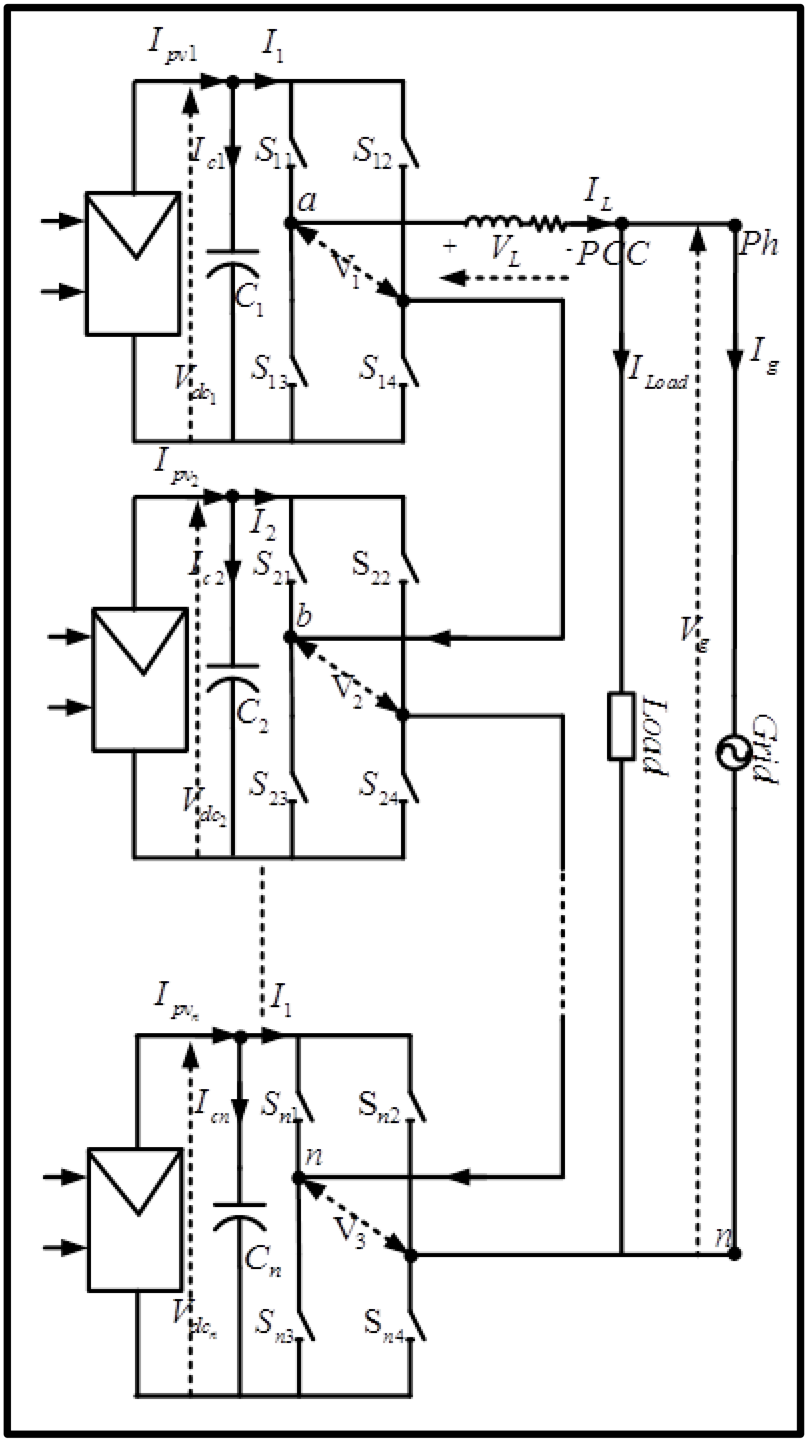


Figure 2.1 Topology for grid connection

As shown in figure 5.1 an L filter is connected between inverter and grid/load to reduce switching harmonics in output current .A local load is connected in parallel to the grid and both of them receives PV power according to the loading or operating conditions.

The output voltage is given by,

$$V_{pj} = (A_{j1} - A_{j3}).V_{cj} = Q_j V_{cj} \tag{5.1}$$

$$j = 1,2,.....N$$

V_{cj} is DC link voltage of the j[th] inverter. Here A_{yy} represents the switching state as in figure 5.2. It shows two discrete values that is ‘1’ to show turn on and ‘0’ to show turn off conditions.

To get linear model, the continuous switching function replaced the discrete switching function in (1) that is S_j € [-1, 1]. The dynamic behavior of the grid connected PV system is given by,

$$\frac{di_o}{dt} = \frac{1}{L}\left(\sum_{j=1} S_j V_j - V_s - Ri_o \right) \tag{5.2}$$

$$\frac{dV_j}{dt} = \frac{1}{C_j}(i_{pj} - S_j i_o) \tag{5.3}$$

$$i_o = i_l + i_g \tag{5.4}$$

Where i_o is the output current of the cascaded H- bridge multilevel inverter, L and R the decoupling inductance and resistance, i_l is the load current and i_g is the grid current.

To select the value of inductor L, Δi_L that is inductor ripple current is to be calculated. If we assume that the fundamental current is zero for inductor L and SPWM (Sinusoidal pulse width modulation) is applied then the ripple current is given by,

$$2\Delta i_l = \frac{V_{dc} - V_{av}}{L} . \frac{d_{1on}}{2} . \frac{1}{f_s} \tag{5.5}$$

Where, d_{1on} is given by the on period of one cycle and f_s is the frequency of switch. When ω̈t lie between 0 and π, we will get,

$$V_{av}(\omega t) = mV_{dc}\sin\omega t \tag{5.6}$$

$$d_{1on}(\omega t) = m\sin\omega t \tag{5.7}$$

Where m is the modulation index.

From equation (5.5),(5.6) and (5.7) the ripple current Δi_L can be expressed as,

$$\Delta i_L = \frac{V_{dc}}{4 f_s L}(1 - m\sin\omega t)m\sin\omega t \tag{5.8}$$

The waveforms of inverter output voltage and ripple current is shown in the below figure 5.2.

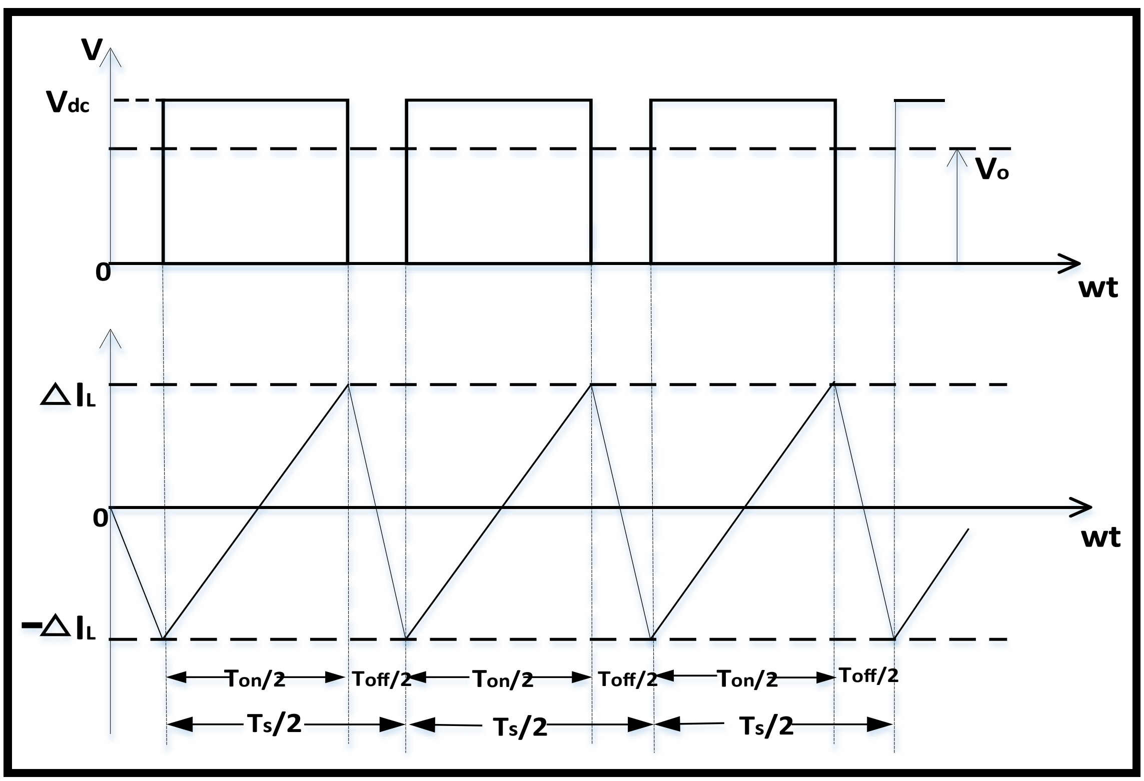


Figure 5.2 Output voltage of Inverter and ripple current Δi_L waveforms.[58]

The maximum ripple current is given by,

$$\Delta i_{L\max.} = \frac{V_{dc}}{4 f_s L} \tag{5.9}$$

With the help of this we can select value of inductor L and the relation between the modulation index and ripple current is given by fig. 5.3.

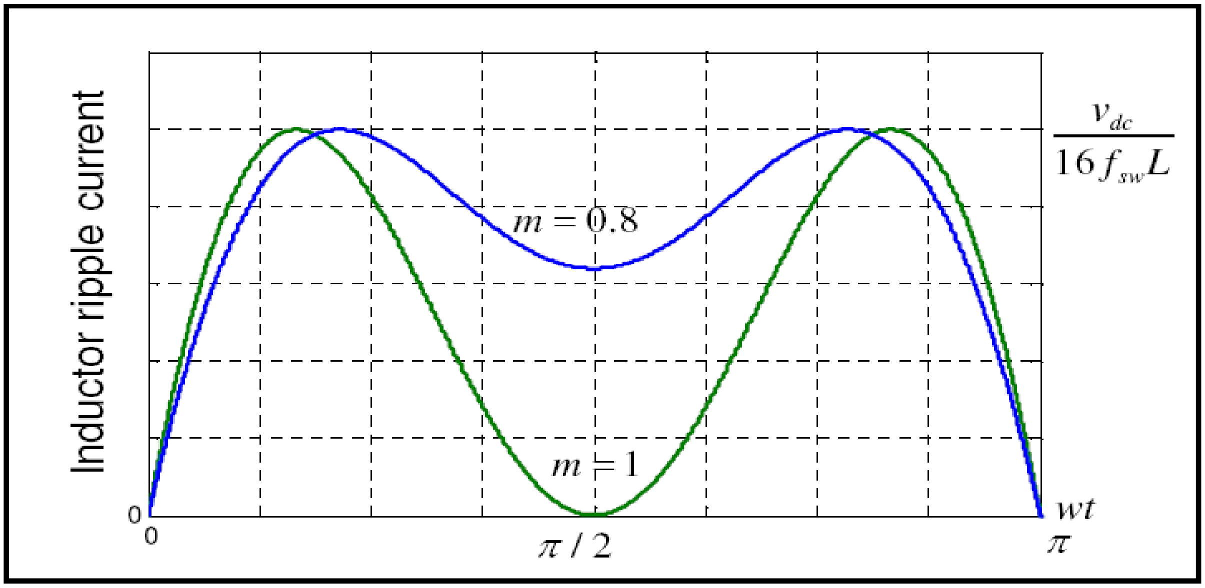


Figure 5.3 Relation between modulation index and the ripple current [58]

To reduce the cost of manufacturing modular design is used in this report. According to this, value of C for individual H bridge inverter will remain same and is given by,

$$C = \frac{P_T}{2n\omega_g V_{dc} V_{rip}} \tag{5.10}$$

Where the total rated power of CHMLI is P_T, V_{dc} is the average voltage across capacitor and V_{rip} is voltage ripple amplitude.

The input of the inverter is PV cell followed by boost converter. Hence V_{dc} is the output of boost converter which is further input of One H Bridge module and it is maximum power point voltage. The ripples should be low at PV module terminals otherwise it gives high fluctuations. The voltage ripple [59] amplitude should be as low as possible that is below 6% of maximum power point voltage. This is to be done to achieve a utilization ratio of 99%.

$$\textbf{Utilization ratio} = \frac{Average\ generated\ power}{Theoritical\ MPP\ power}$$

5.2 PV Panel mismatches

Individual MPPT control is necessary in single phase cascaded H bridge multilevel inverter. The overall efficiency of PV system will decrease if any mismatch will occur among the PV strings. This will happened only if the tracking of maximum power point of each string will not be done individually.

The MPP of each PV string is different due to many reasons such as different temperature, aging of PV panels and unequal irradiance. The application of cascaded H Bridge MLI in medium and large grid connected system can be realized by tracking maximum power point of each PV string individually. Hence in this chapter one control scheme is mentioned which self explains the necessity of individual MPPT control.

5.3 Control Scheme

The better utilization of Photo voltaic module can be done without any sacrifice. Due to the above mentioned benefit cascaded H Bridge MLI can extensively be used in medium as well as large grid connected PV system. The power quality may be affected by the impact and higher penetration of PV system.

The power quality in grid and performance of distribution circuits can be maintained good by controlling reactive power. Hence to fulfill this thing a control scheme is proposed which is shown below.

5.3.1 Individual MPPT control

To improve the efficiency of photo voltaic system and remove the bad effect of the mismatches the PV strings should be operated at different voltages so that maximum energy can be brought out. Individual voltage control is possible in Cascaded H Bridge Multilevel Inverter as it uses separate DC links.

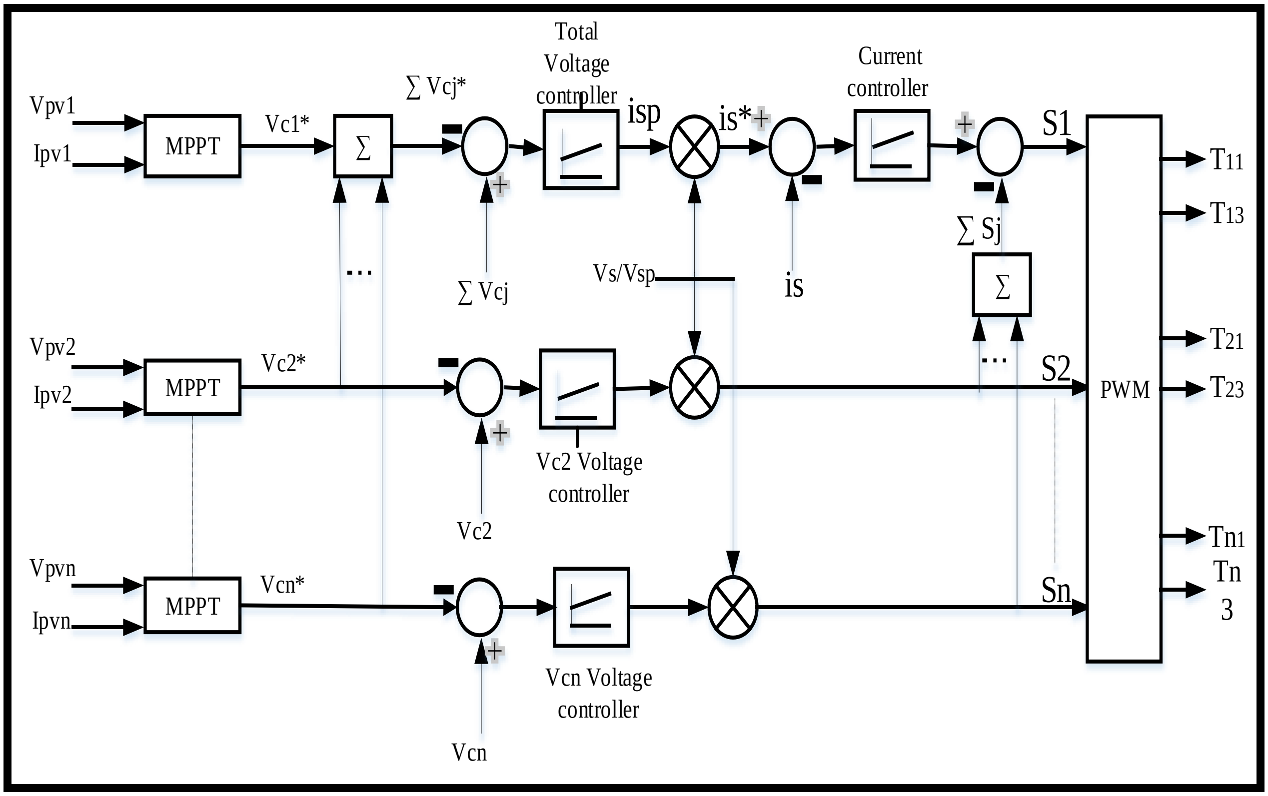


Figure 5.4 control strategy [56]

Figure 5.4 explains the control strategy used to control the DC link voltage to get High power as well as fewer harmonic in output. With this the quality of output improves and it gives modulating signal which is quite near to sine wave.

In these to generate DC link voltage reference MPPT controller is used in each string. The input of MPPT is photo voltaic current and photo voltaic voltage. The sum of the individual DC link voltage is compared with the reference voltage. The error is fed to the total voltage controller which is nothing just a PI controller. This PI controller is used to determine active current provide by the multilevel inverter.

The output of total voltage controller gives the reference current. Then this reference current is compared to grid current and fed to current controller. It give the total modulation index for each inverter.

The voltage V_{dc2} to V_{dcn} is individually controlled through (n-1) loops. Modulation index for one H Bridge module is obtained by individual voltage controller. This modulation index is nothing but to show the modulating signal. Then Phase disposition SPWM scheme is applied to compare carrier and modulating signal. Then the output signal is applied to control the switching devices of each H-Bridge.

By varying the phase and magnitude of the first cell or second cell the power factor can be controlled. Input inductance and number of cells can limit the power factor control [56].

5.4 Conclusion

In this chapter, a single-phase modular cascaded H-bridge multilevel inverter for grid connected PV system has been presented. the inverter has the possibility to reduce the adverse effect of PV mismatches due to the cascaded configuration, in medium and large grid-connected PV systems. A control scheme with independent MPPT control has been proposed.

Chapter 6

THREE-PHASE CASCADED H-BRIDGE MULTILEVEL INVERTER FOR GRID CONNECTED PHOTOVOLTAIC SYSTEMS

In medium and large grid connected photovoltaic systems, three phase inverters are widely used. This trend is increasing day by day that large grid is integrated to photovoltaic systems. The maximum energy can be draw from the PV panels by employing individual MPPT control in each string. In compare to other topologies this topology is highly efficient and reliable. Its design is modular in nature which reduces the cost of the system as well as gives flexibility to the system. [60]

The multilevel inverter topology for the Photovoltaic system connected to three phase system is discussed in this chapter. To avoid the panel mismatches issue individual MPPT control is required. Use of separate DC link is necessary to achieve independent voltage control. With the help of this technique utilization of Per PV module can be done in better way. To achieve the above mention phenomenon as well as for active and reactive power control one control scheme is proposed in this chapter.

6.1 System description

The modular design of cascaded H bridge multilevel inverter is shown in figure 6.1 in which PV system is connected to the grid. Each phase consist of series connection of number of H bridge inverters and string of PV panels supply to the DC link of inverter. Between grid and cascaded H bridge multilevel inverter inductors are used to reduce harmonics in the current and it also helps to achieve unity power factor.

Mainly distributed MPPT control is used in three phase cascaded H Bridge multilevel inverter [61] . MPPT controller helps to achieve DC link voltage reference in each module. Many MPPT methods has been used to harvest maximum energy from PV panels but in this report incremental conductance method is used [62-63] whose decision based upon the previous value of the tracked voltage and current.

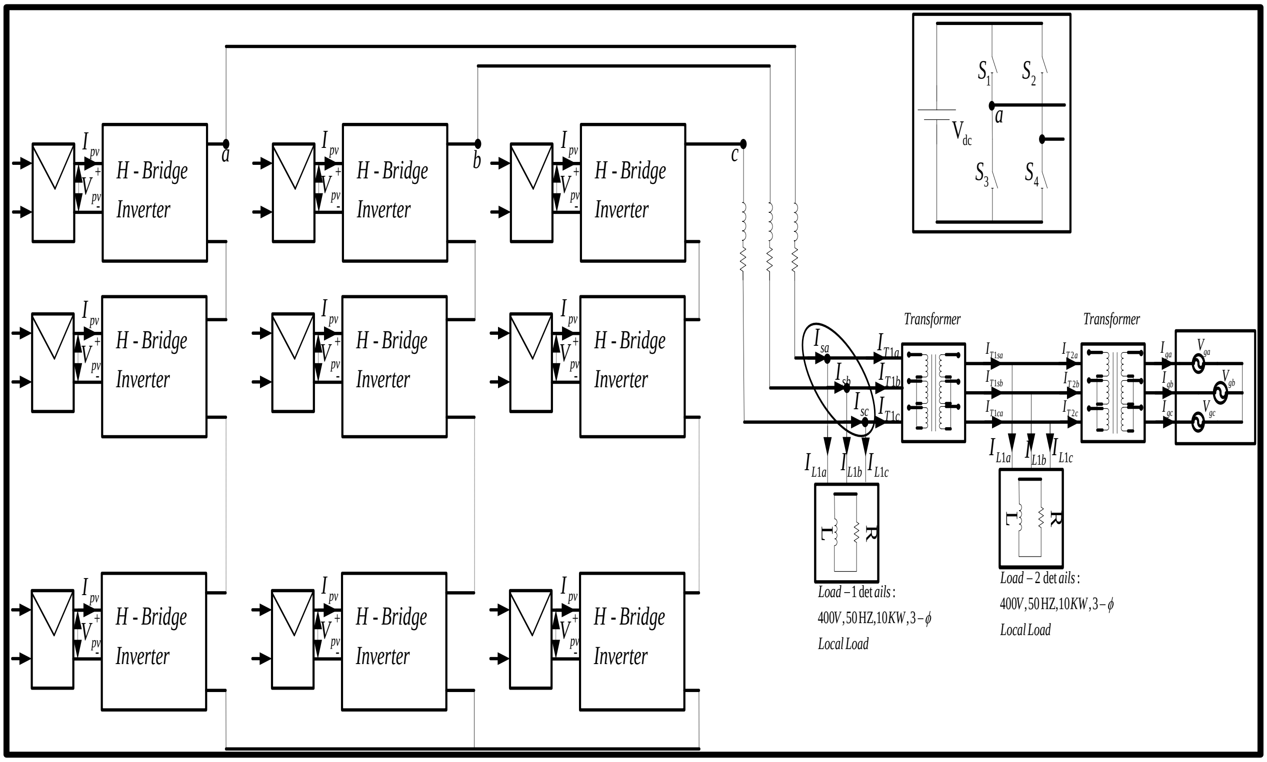


Figure 6.1 Topology for the three phase grid connected system

6.2 Control Scheme

In single phase system already explained the necessity of individual MPPT control. This mainly focuses upon the increased efficiency and reduced the PV mismatching effect. In single phase the issue of mismatching was not up to that much extent but in three phase Grid connected photovoltaic system it can create severe problems. Even this problem may lead to supply unbalanced power to grid.

The input power of each phase will not be remain same if photovoltaic mismatching occurs between the phases. As the voltage which is coming to the grid is balanced but the power is different which result in unbalanced current. The unbalanced current to the grid is not allowed from utility standard point of view other than that it is harmful for grid too.

A control scheme is proposed to overcome the mismatching issue and to balance the grid current. The scheme is shown in figure 6.2.

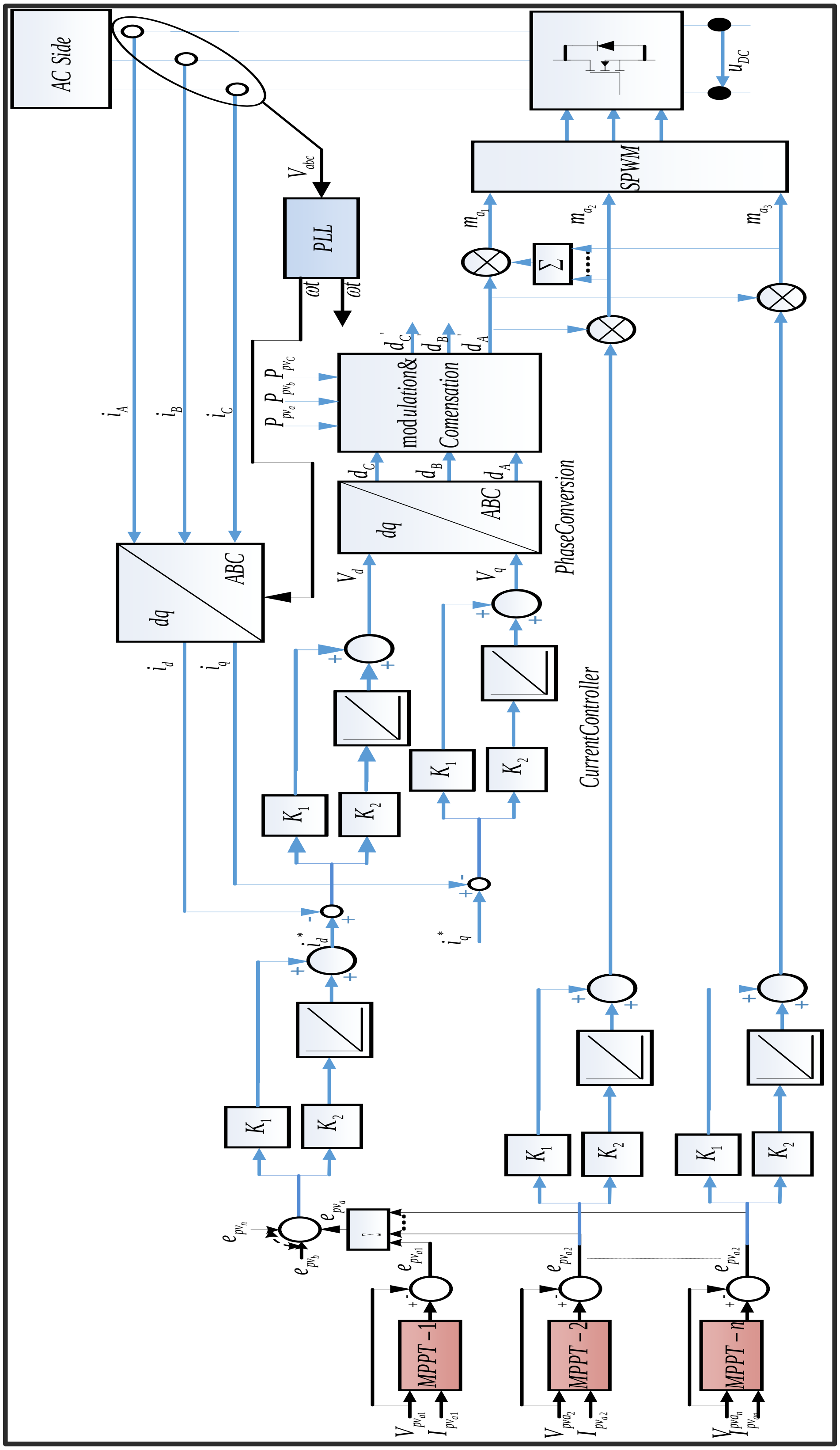
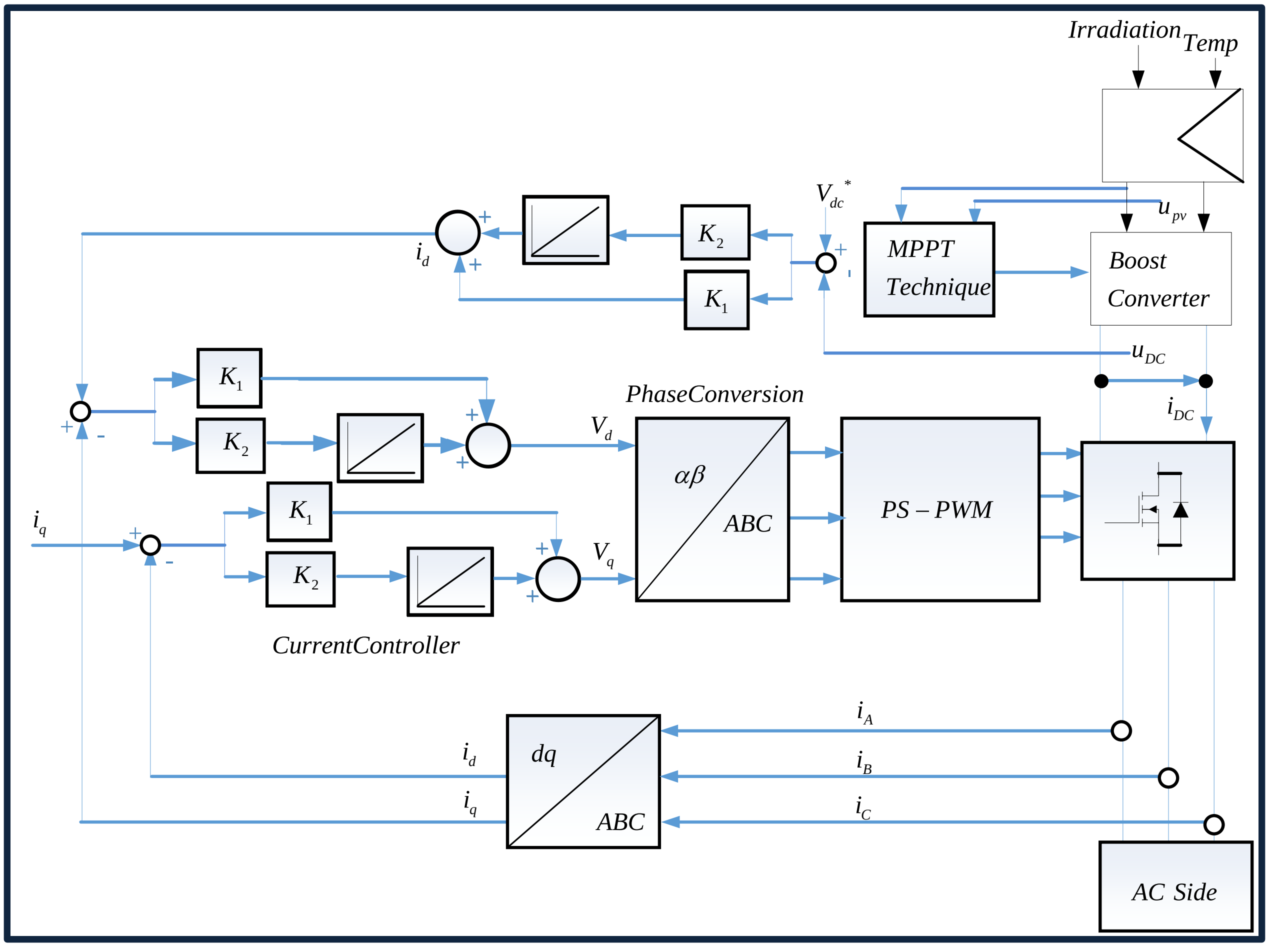


Figure 6.2 Control scheme for three phase H bridge multilevel inverter



Implemented Control Scheme

6.2.1 Individual MPPT control [60]

The scheme used in single phase system that is individual MPPT control is extended for three phase system. In classical control scheme the currents taken from grid are converter from abc to dq form means from three phase system to hypothetical two phase system. When these currents are regulated through PI controller it generates modulation index and this is again converted into its original form.

The control scheme proposed in this report is extension of above mentioned phenomenon. For cascaded H bridge inverter individual MPPT control for any one phase for example phase a is shown in figure 6.2.

To generate the DC link reference voltage MPPT controller is added in each H-Bridge module. This reference voltage is compared with the DC link voltage of Inverter. After this it generates an error signal and then the sum of error signals of Series connected H Bridge inverter is controlled through PI controller. Pi controller generates the active component of current which is known as I_{dref} .

In this simulation the reactive power component I_{qref} is taken as constant value that is zero. With the help of reactive current calculator I_{qref} can be generated, if reactive power compensation is required.

The remaining voltages $V_{dc1a}$to V_{dcna} could be individually controlled through n-1 loops. In individual loop voltage controller is there to generate the modulation indices. In first loop errors of all the phases is added and fed to the PI controller which generate the reference active component of current. When reference active and reactive component of current are compared to the active and reactive current taken from grid then again it generates a error signal. These signals are fed to the respective PI controllers to generate dq component. Again dq to abc converter is used to convert it in its original three phase form. Here multiplication of modulation index which are generated in (n-1) loop takes place. By subtracting the remaining modulation indices modulation index for the first H Bridge can be carried out.

Control scheme for remaining phase b and c will remain same. These modulation indices are used to generate modulating signal and fed to (PS-SPWM) switching scheme to generate switching pulses. These switching pulses are used to control to the switching devices of each H Bridge.

To manage different voltage levels 3n voltage loops are necessary and to manage the current reference I_{dref} total voltage loop is required.

6.3 Conclusion

The multilevel inverter topology for the Photovoltaic system connected to three phase system is discussed in this chapter. To avoid the panel mismatches issue individual MPPT control is required. Use of separate DC link is necessary to achieve independent voltage control.

Chapter 7

FPGA BASED DESIGN PROCEDURE

7.1 FPGA Design Flow

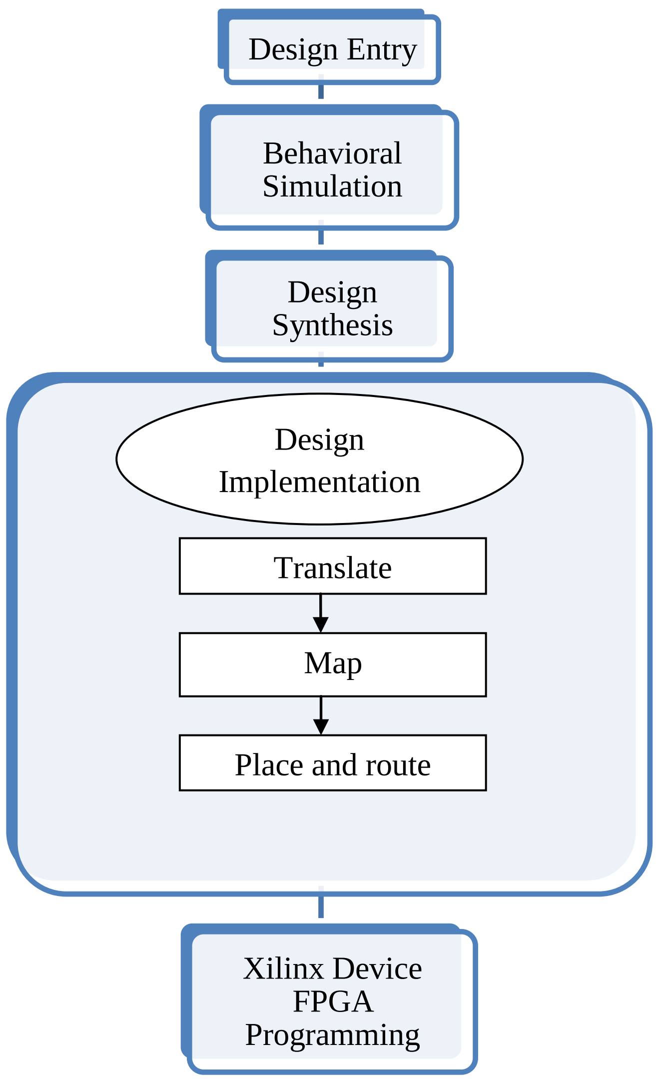


Figure 7.1 Control scheme for three phase H bridge multilevel inverter

7.2 FPGA Basics

The field programmable gate array (FPGA), is a array of logic cells or modules. It can be reprogrammed according to the requirement of user. Designing can be done according to the requirement and changes too. It is most suitable for embedded design because its prototype cost is negligible as well as it provides instant manufacturing turnaround.

7.2.1 Design Entry

To design on FPGA this is first towards implementation. In this step the VHDL (very high speed integrated Chip Hardware Description Language) code of PWM generator was written using software Xilinx ISE 10.1. To write the code mainly structural modeling is used. After that to see whether the code is written properly or not Syntax check was performed.

7.2.2 Behavioral Simulation

The next step towards design is behavioral simulation. This step is known as verification step as this is used to verify that whatever design entered is functionally correct or not. This simulation is also known as RTL simulation. For this simulation was seen in Xilinx ISE Simulator and VHDL Test bench was written for PWM generator architecture. After that it s verified that it is functionally correct or not.

7.2.3 Design Synthesis

Xilinx XST which is a part of ISE software is used to synthesize VHDL code of PWM generator. To perform the operation of synthesis there is a option of synthesis in process tab of Xilinx ISE. The process of design synthesis is used to optimize the design architecture selected.

The net resultant list is saved to an NGC file. After that synthesis report is generated. This report gives information about logic blocks used and also about the device utilization of the design architecture synthesized. Synthesis design basically maps the behavioral design to gate level design.

7.2.4 Design Implementation

Design implementation consists of following three steps:-

- Translate

- Map
- Place and Route

Before translating the design, User constrained file (UCF) is written to assign pin configuration of the FPGA to the PWM generator I/Os. Translate merges all UCF files and after synthesis net list is generated into Xilinx design file.

Mapping is important step of design. It is used to fit the design into the available resources of target device that is FPGA.

Last step of design implementation is Placing and routing which produces NCD output file. This step places the logic blocks of the design into FPGA. It routes the logic blocks together so that it can meet timing requirements and occupy minimum area.

7.2.5 Xilinx device (FPGA) programming

One of the process tab of Xilinx ISE is a generate programming file. It is used to convert the NCD file generated after routing to BIT file. It produces BIT stream for Xilinx device configuration. This bit file is used to program the FPGA.

7.2.6 Configuring target device

There is a option of Generate Target PROM/ACE on the process tab of XILINX ISE which converts the BIT file to the PROM or ACE file. This PROM or ACE file can be downloaded directly into the FPGA memory cells.

FPGA should be properly connected to the PC. After PROM or ACE file downloaded into the FPGA, the FPGA is ready to be used as PWM generator. By different input combination output variation of FPGA can be seen.

7.3 Conclusion

In this chapter we studied about the FPGA which is used to generate pulses for hardware. This chapter explains about its design flow. With the help of this programming can be carried out.

Chapter 8

SIMULATION RESULTS

In this chapter, the simulation result implemented in MATLAB SIMULINK is presented. This chapter mainly consists of simulation of solar PV module, DC-DC Boost converter and a 5- level H- bridge multilevel inverter for different loads.

8.1 Solar PV Module

Simulink model of solar PV module is not directly available in MATLAB 2009a version. So we have to develop the MATLAB simulink model for solar PV module by using mathematical modeling of solar PV module. But Solar PV module Simulink model is directly available in MATLAB Latest versions like 2010a onwards,

MATLAB simulink model of total PV module has developed as shown in following diagram. Under varying temperature conditions Solar PV module develops variable DC Voltage.

Figure 8.1 shows the Simulink model diagram of PV module. Irradiance, Temperature and Short circuit currents are inputs to the PV module and this model is mathematically modeled in MATLAB by using basic mathematical equations of PV module.

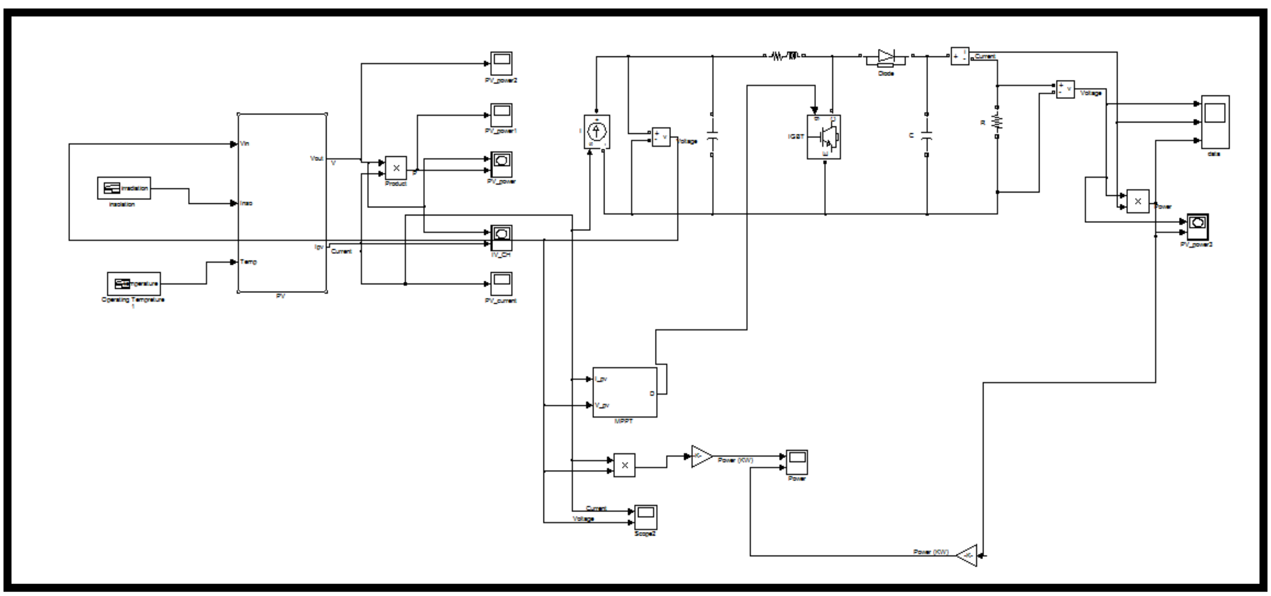


Figure 8.1 Simulink model of Solar PV Cell

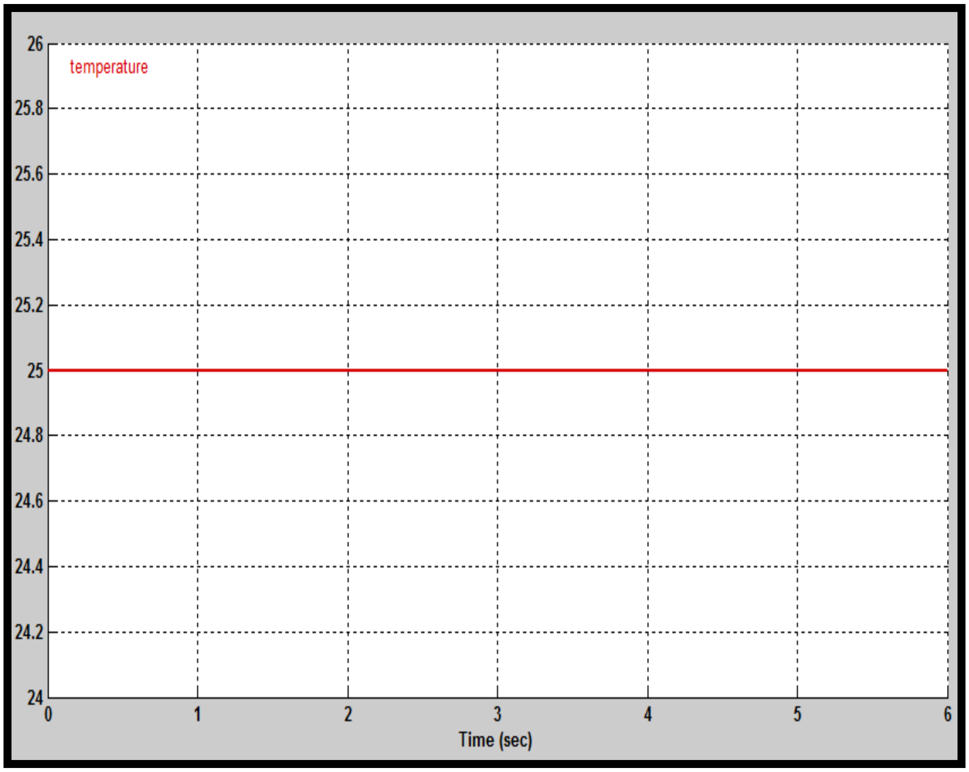


Figure 8.2 Temperature Variations at input side Solar PV module

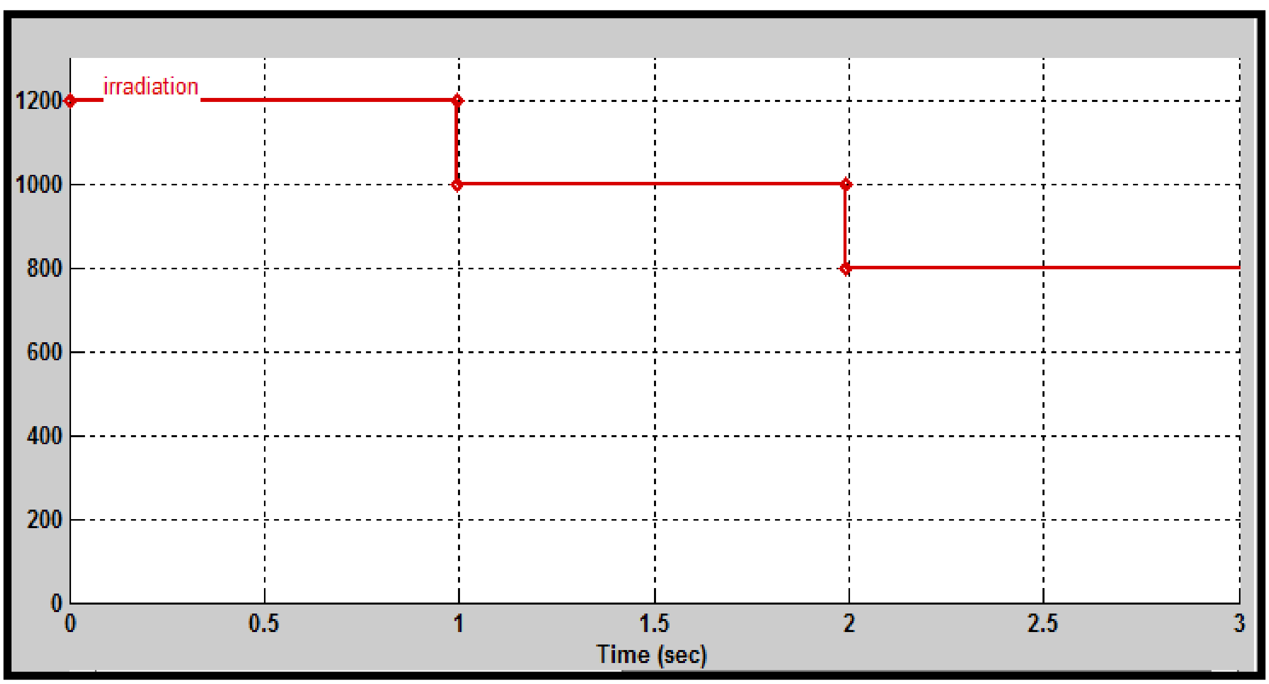


Figure 8.3 Irradiation variation at input side solar PV module

Data Sheet Values		Estimated Parameters	
I_{sc} (Short circuit current)	3.82A	I_{ph} (Photon current)	5.9602 A
V_{oc} (Open circuit voltage)	44.11V	I_0 (Diode current)	0.0312 µA
V_{mpp} (Voltage at maximum power)	35.62	A (Diode factor)	1.30
I_{mpp} (Current at maximum power)	3.595A	R_s (series resistance)	0.038Ω
N_s (No. of Series connected solar cells)	96	R_{sh} (Shunt resistance)	993.5Ω
Temperature Coefficients			
K_i (Temperature Coefficient for current)	0.015%	K_V (Temperature Coefficient for voltage)	-0.21%

Table 8.1: Datasheet values of Solar PV module

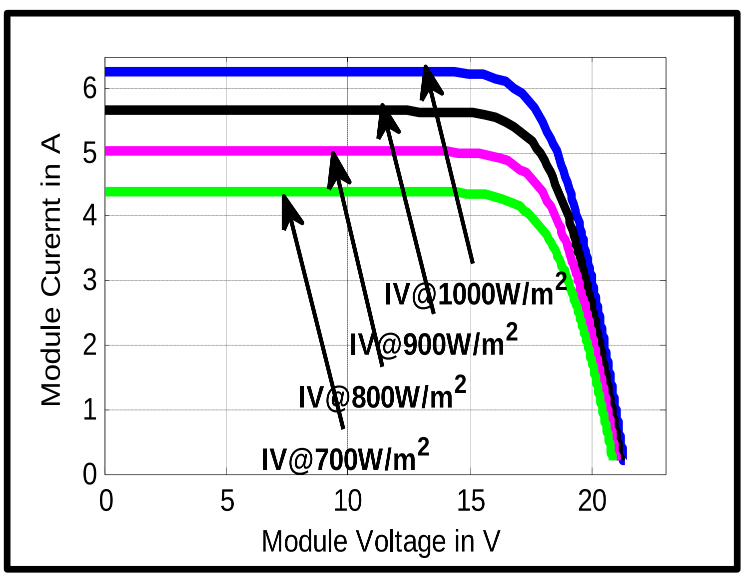


Figure 8.4 Module I-V Characteristics with change in irradiation

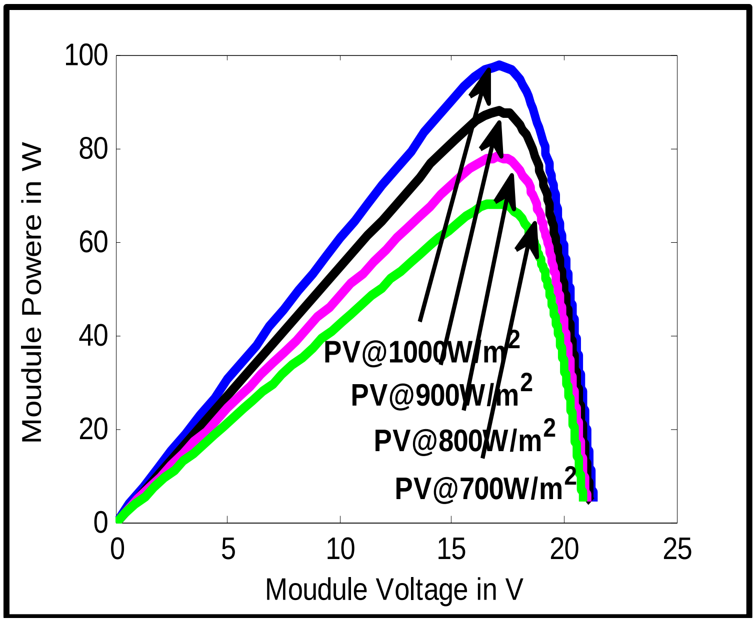


Figure 8.5 Module P-V Characteristics with change in irradiation

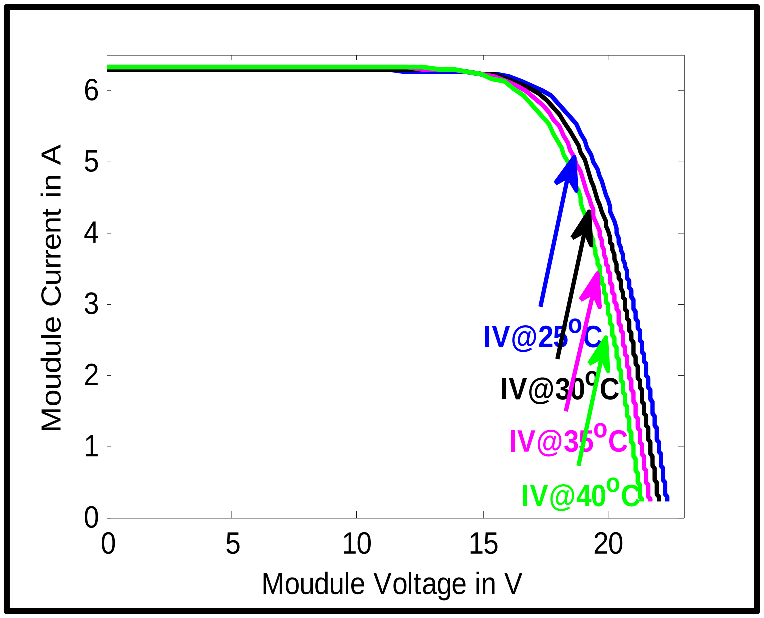


Figure 8.6 Module I-V Characteristics with change in temperature

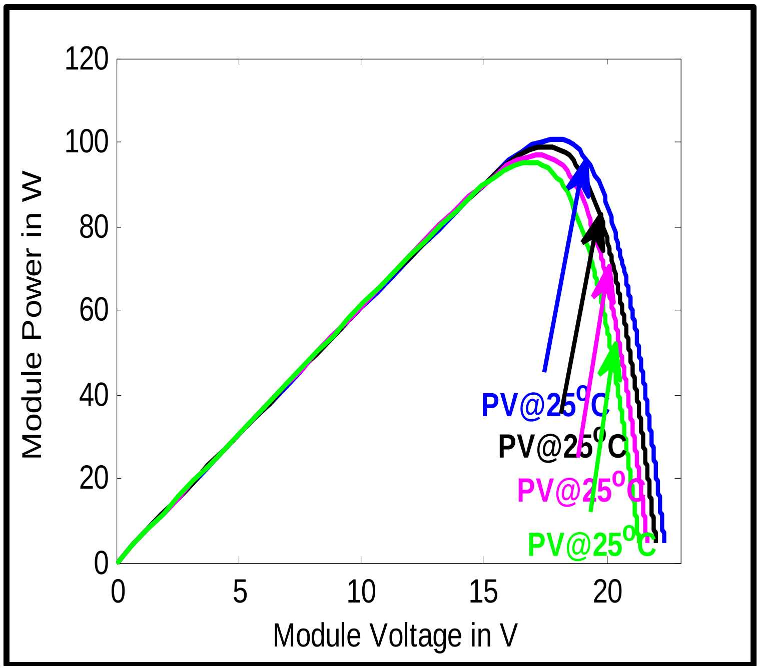


Figure 8.7 Module P-V Characteristics with change in temperature

8.2 BOOST Converter Results:

DC- DC Converter is designed for 24 v to 48 v with the following design element values.

Drain to source resistance rDS = 0.1800

Inductor L = 7.000e-004 H

Inductor Internal resistance rL = 0.1900

Capacitance C =4700 µF

Capacitor resistance rC = 0.1110

Diode Forward resistance RF = 0.0720

Input Voltage V_i = 24

Output Voltage V_o = 48

Output Power P_O = 50

Switching Frequency F_S = 10000

T_s = 1.000e-004s

Duty Ratio D = 0.5

Output Current I_o = 1.0417

Load resistance R_L =46.0800

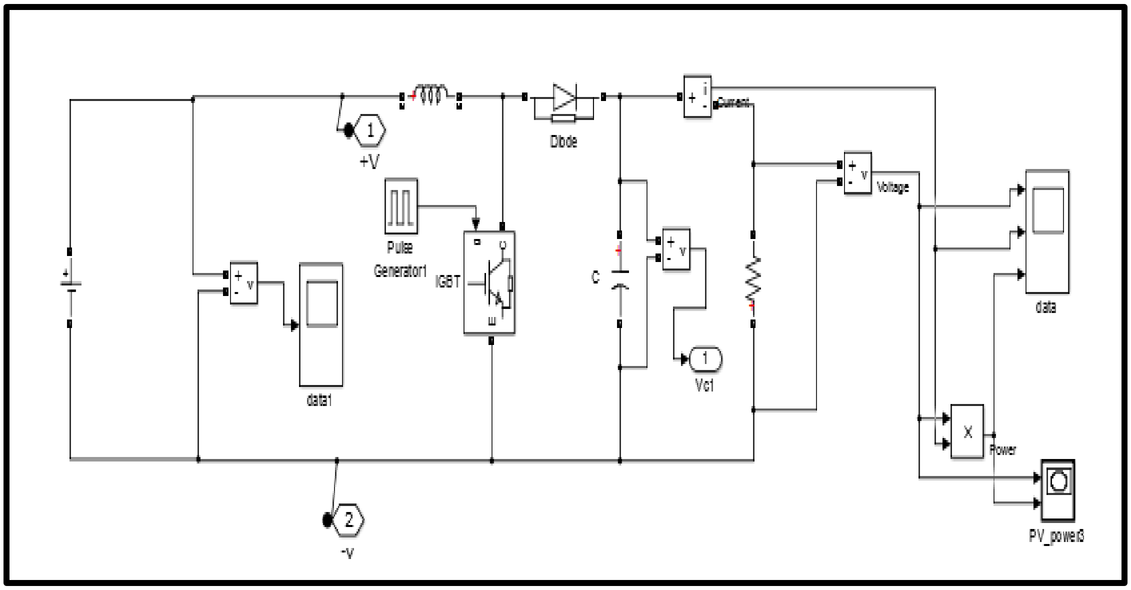


Figure 8.8 Simulink Model of BOOST Converter

Figure 8.8 depicts Simulink model diagram of Boost DC – DC converter by considering the parasitic elements

8.3 5- Level H Bridge Multilevel Inverter

5-Level H Bridge Inverter is developed in Matlab / Simulink. To drive the switches in H Bridge Multilevel Inverter gate pulses are needed. These gate signals are produced by level shifted Sinusoidal Pulse width modulation technique. By using above mentioned technique gate pulses are produced in FPGA set. The output terminals of H Bridge inverter are connected to grid. Under this load condition produced inverter voltage and current waveforms and their THD waveforms are Shown below.

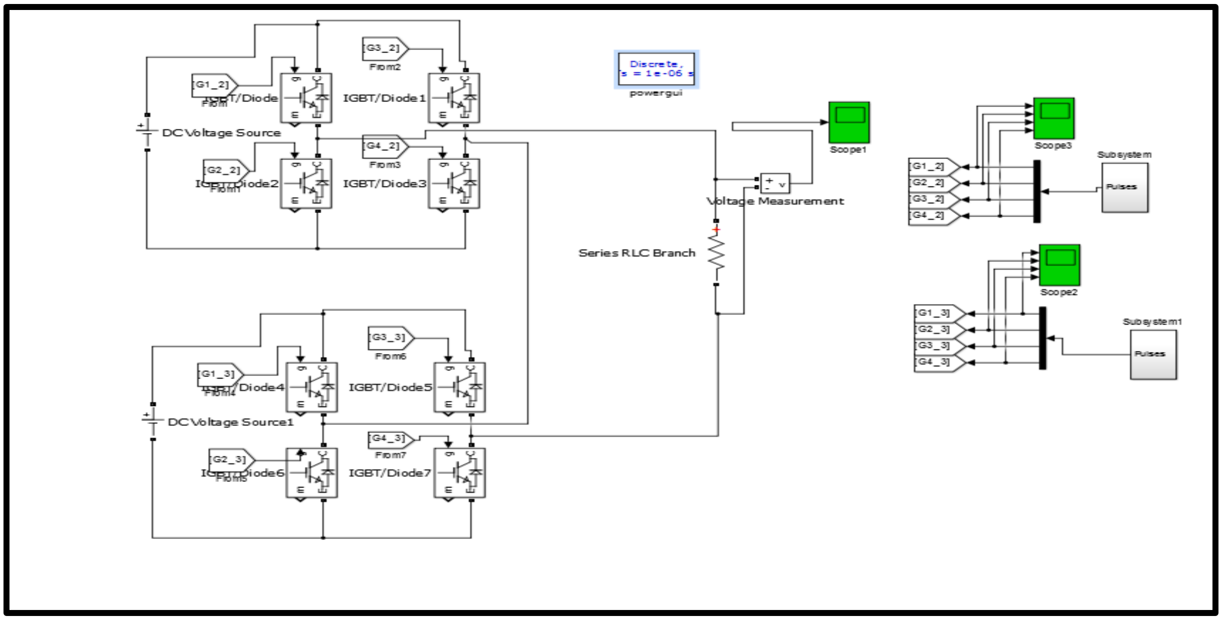


Figure 8.9 Simulink Model of 5- level H Bridge Inverter

8.3.1 Open Loop Simulation of H Bridge Inverter

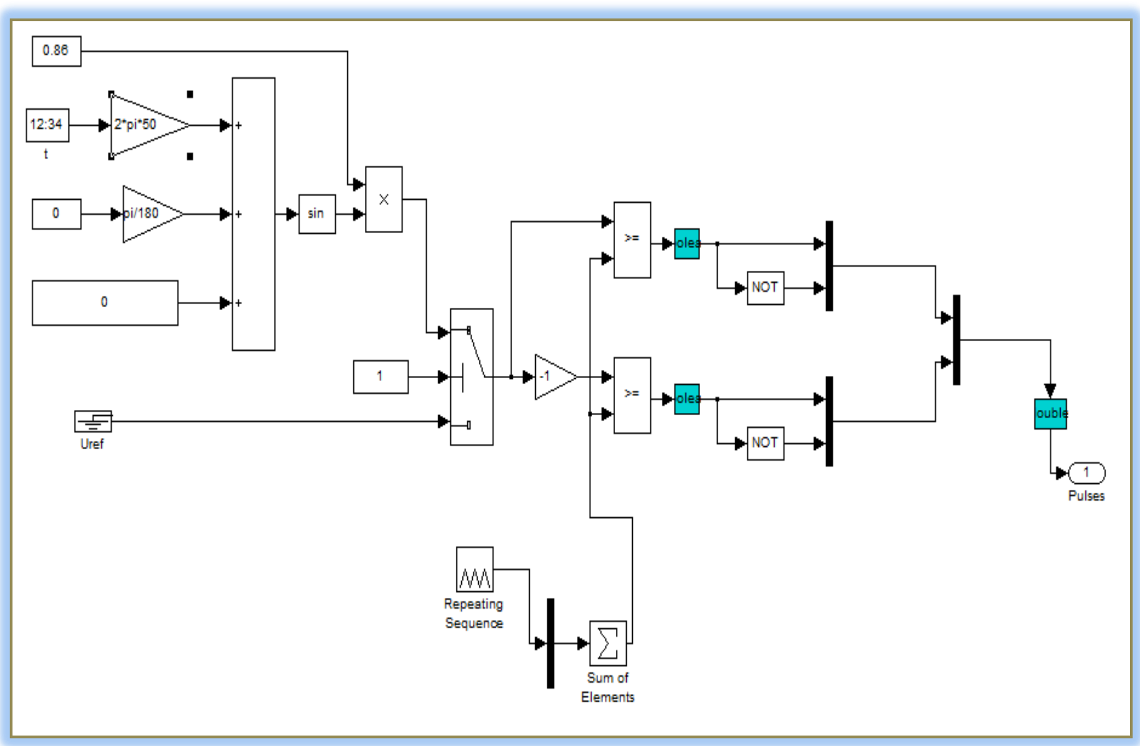


Figure 8.10: Control Scheme of 5- level H Bridge Inverter

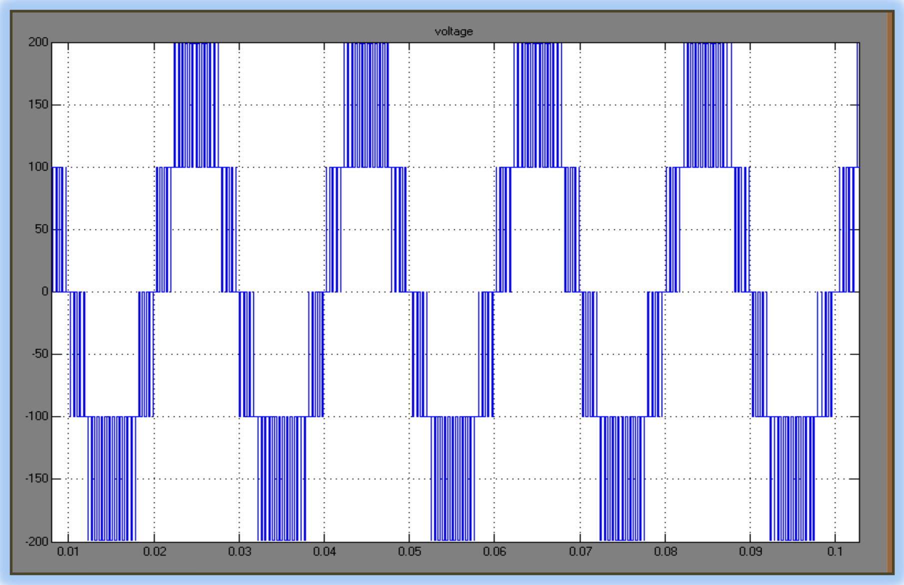


Figure 8.11 : Output Voltage of 5- level H Bridge Inverter

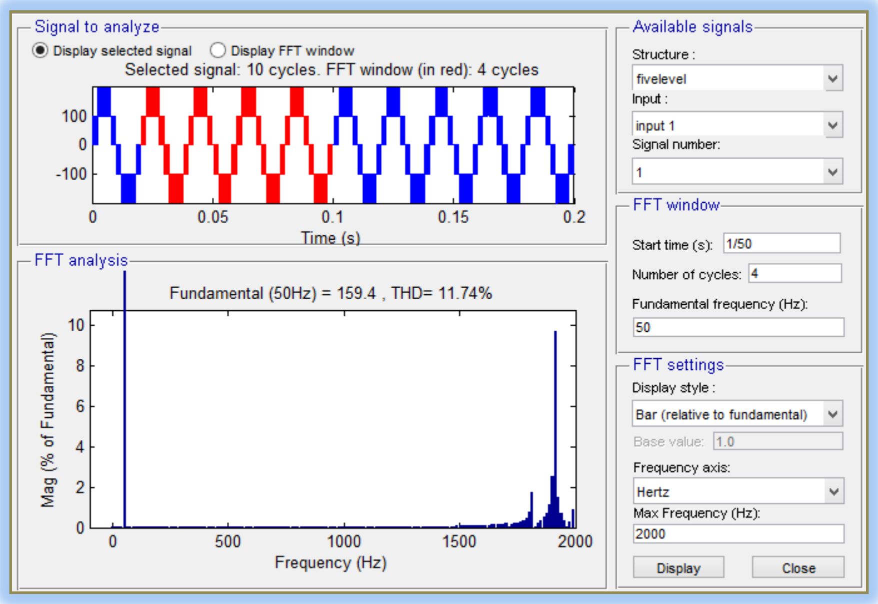


Figure 8.12 :THD Analysis of output Voltage of

5- level H Bridge Inverter

Voltage THD levels of 5- level H bridge Inverter are mentioned in table 8.2:-

H Bridge	5-level
Voltage THD	11.74%

Table 8.2: Voltage THD levels of 5- level H bridge Inverter

8.3.2 Closed Loop Simulation of 1-phase H Bridge Inverter

A PV-MF165EB3 module has been considered for simulation and modeled in Matlab Simulink environment using the mathematical equations discussed in chapter 2. The parameters of the PV modules are given in table III. Each PV strings has been designed by connecting 15 such modules in series and 4 such strings are connected to form a PV array of 10 kW under standard environmental condition. The grid-connected photovoltaic system, represented in Figure has been implemented using this 10 kW PV array. The parameters used in the simulation of grid connected VSI and the boost converter has been provided in table IV. The single phase inverter is operated in unipolar PWM mode with switching frequency of 10 KHz. The output of the VSI is connected to the grid trough an inductor. The performance of the entire control scheme of for grid connected PV system has been examined. Two operating cases are considered in the following section.

Datasheet parameters	Values	Datasheet parameters	Values
I_{mpp}	6.83 A	I_{sc}	7.36 A
n_s	50	V_{oc}	30.4 V
k_i	0.057%	V_{mpp}	24.2 V
k_v	-0.346%		

Table 3 Datasheet parameters of PV-MF165EB3 module

parameters		Values
Dc link voltage V_{dc}		550V
Grid voltage V_g(RMS)		230V
Filter inductor and transmission line	Inductance L	6 mH
	Resistance R	1 Ohm
Switching frequency f_{sw}		10 KHz
Supply frequency f_s		50Hz

Table 4 Simulation Parameters of System

8.3.2.1 STEADY OPERATING CONDITION WITH STANDARD ENVIRONMENTAL CONDITION

In this case the standard environmental conditions are considered. The solar irradiance and operating temperature are taken to be of 1kW/m^2 and 298K respectively. The tracking response of the proposed control strategy for boost converter has been verified with ramp signal. The response of the converter has been shown fig. 8.13. This figure demonstrates the good tracking response of the proposed control strategy. Fig. 8.14 shows the output current of the simulated grid connected PV system along with its reference value. As mentioned earlier the grid voltage and the supply current by single phase VSI should be in phase with each other. Fig. 8.15 shows the phase relationship between grid voltage and supplied current. The control strategy must ensure a THD level, which is less than 5% .The frequency spectrum of inverter output current has been shown in fig 8.16. The THD is 4.17%, which is within the limit as specified earlier.

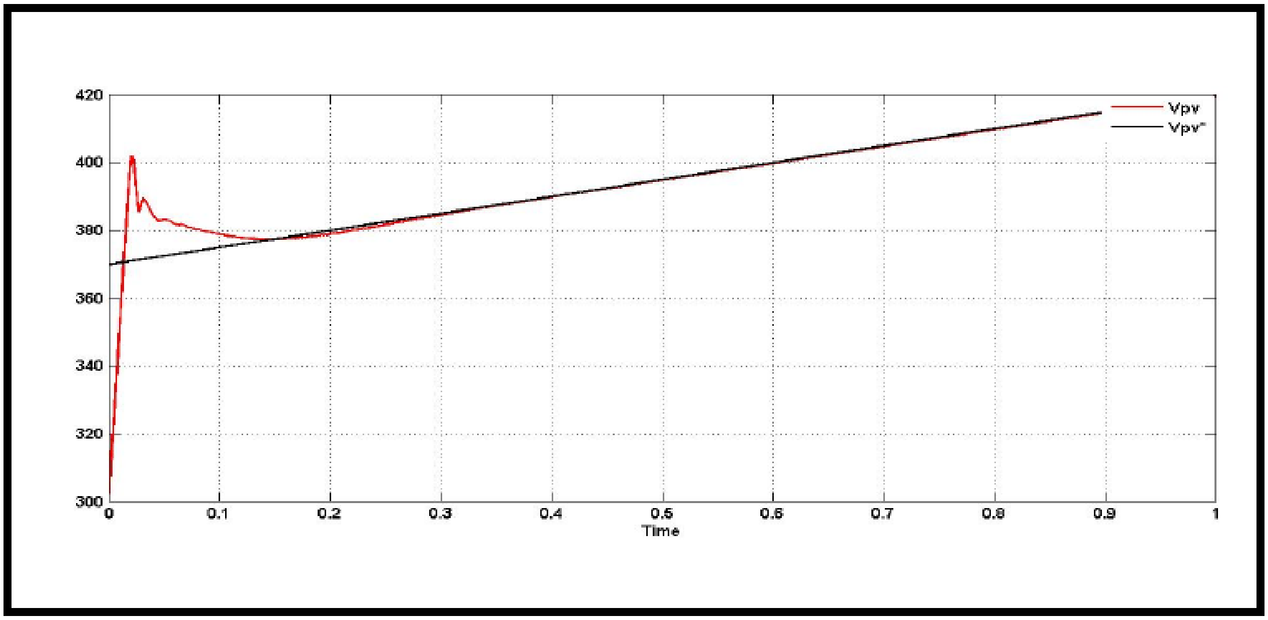


Figure 8.13 Tracking Response of Proposed Controller for Boost Converter for Ramp Input

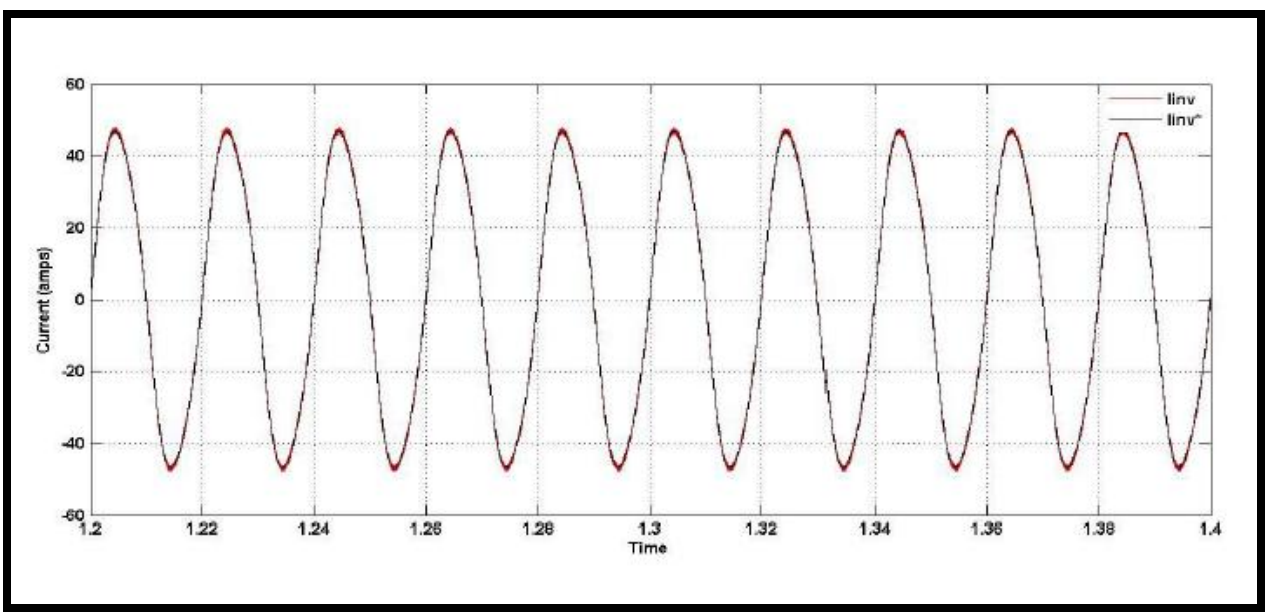


Figure 8.14 Inverter Output Current under Standard Environmental Condition

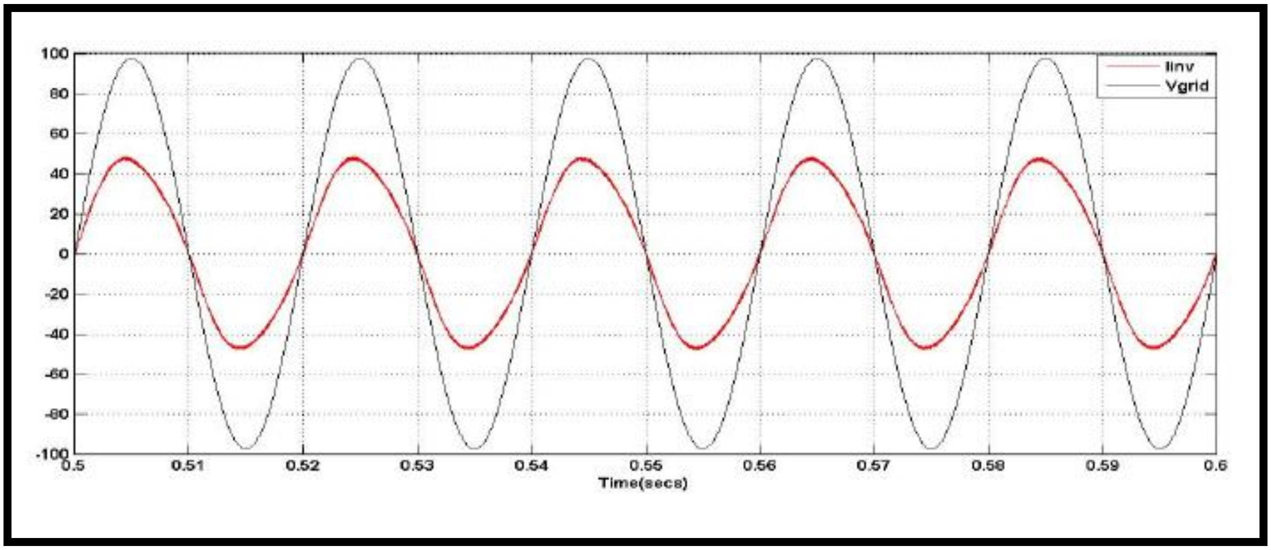


Figure 8.15 Scale Grid voltage and Supplied Current by VSI

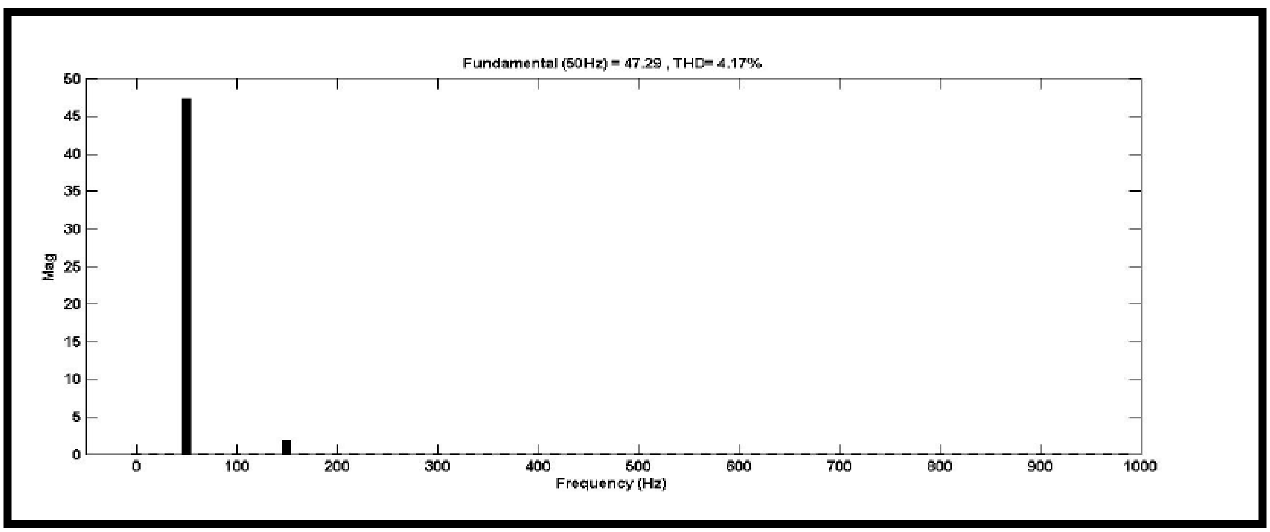


Figure 8.16 Frequency Spectrum of Inverter Output Current

8.3.2.2 PV SYSTEM SUBJECTED TO CHANGE IN ATMOSPHERIC CONDITION

The intermittent nature of solar radiation makes the operating point of grid connected PV system random. The proposed controller for DC/DC converter should track the maximum power point as quickly as possible. The changes in the PV array operating point appears as transient for the proposed controllers. The performance of the controller should be adequate during these transients. In this section the transient response of the proposed controllers that is the controller for boost converter and controller for VSI has been examined in this section. The intermittent nature of solar energy is been considered by varying the solar radiation tern G in (2).The solar radiation has been kept at $1000W/m^2$initially. At time t = $0.5sec$ the radiation has been changed to $1250W/m^2$andthen decreased by $750W/m^2$ at time t = $1sec$. Again the irradiance level has been increased by$250W/m^2$ at $1.5sec$. This leads to a change in operating point of PV array changes.

The change in radiation level causes disturbance in the operating point of the boost converter. The proposed dual loop controller for boost converter should follow the reference value V_{pv}^* as closely as possible. In fig. 8.17 terminal voltage across the PV array V_{pv} has been shown along with reference value. This ensure a good dynamic response for rapid and large changes of irradiance (500% at t = $1sec$).

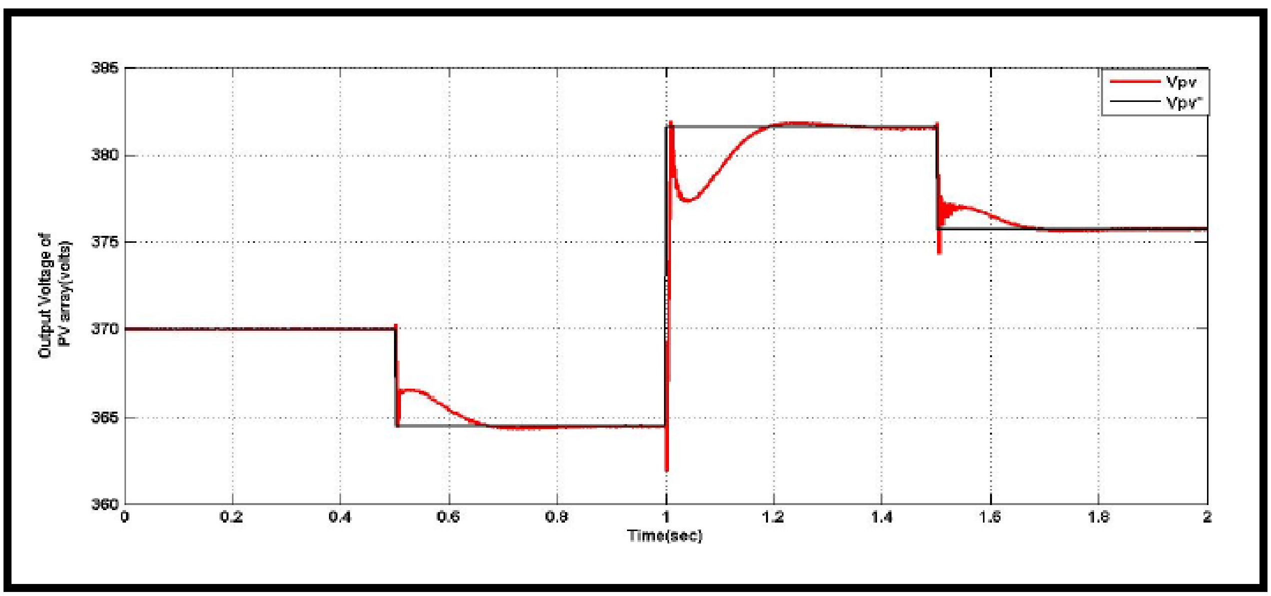


Fig. 8.17 Tracking Response of Proposed Controller for Boost Converter

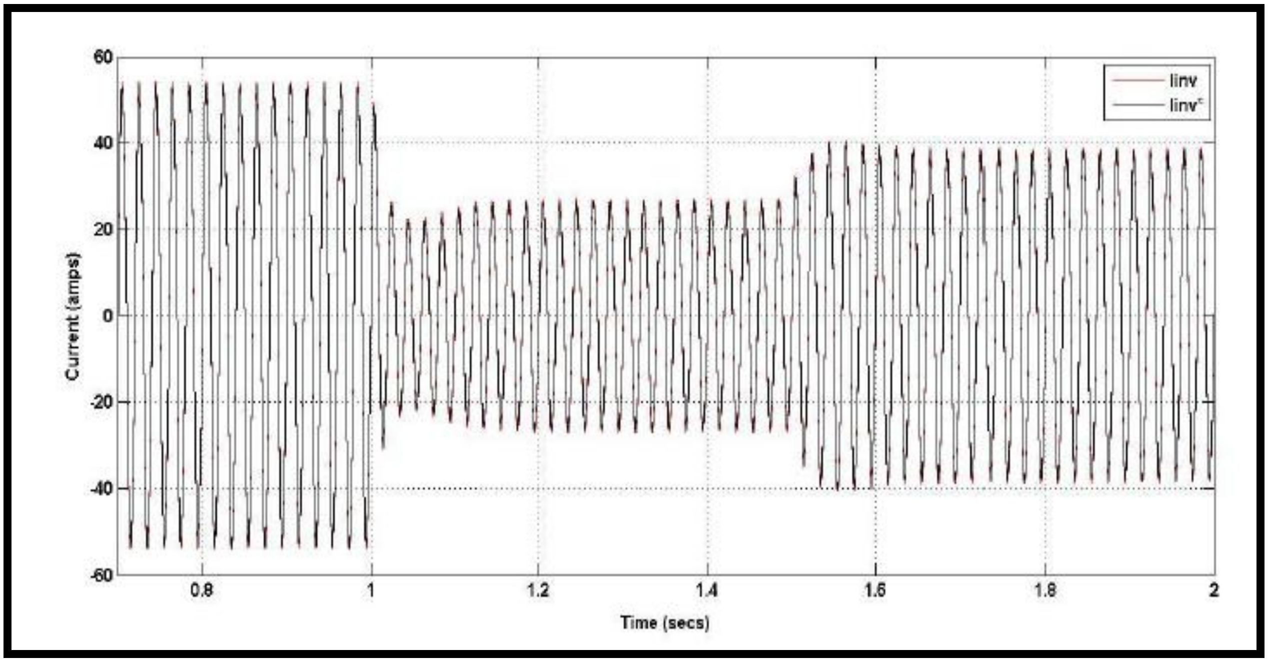


Figure 8.18 Tracking Response of Proposed Nonlinear Controller

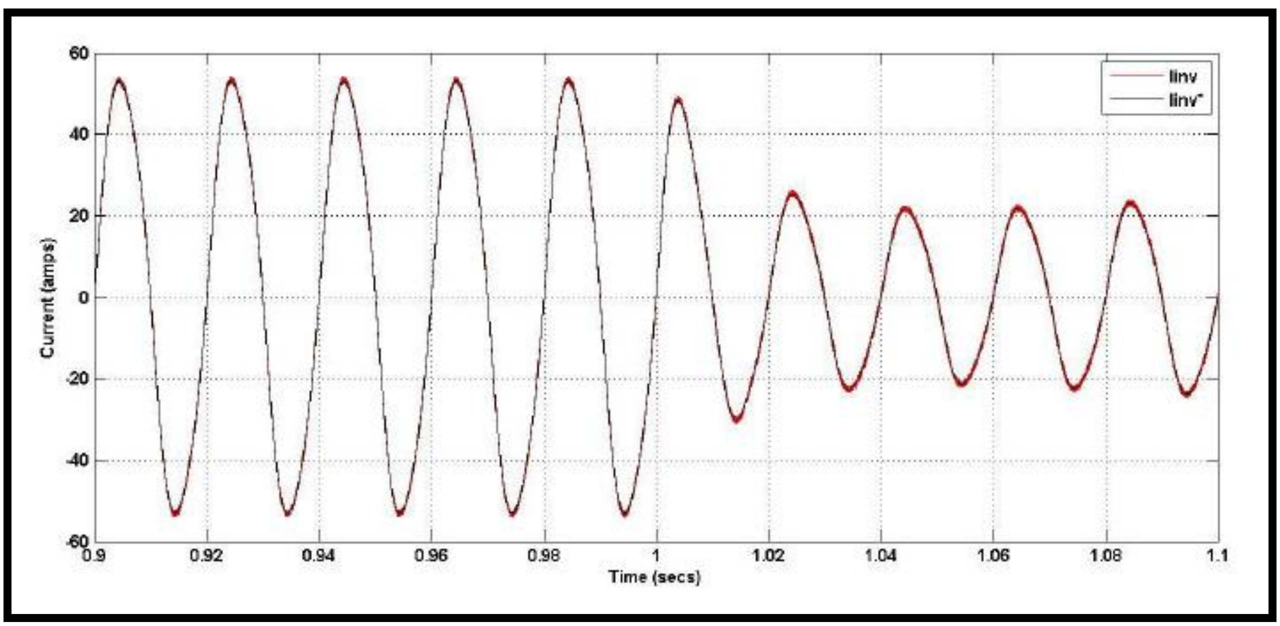


Figure 8.19 Magnified Tracking Response of Proposed Nonlinear Controller

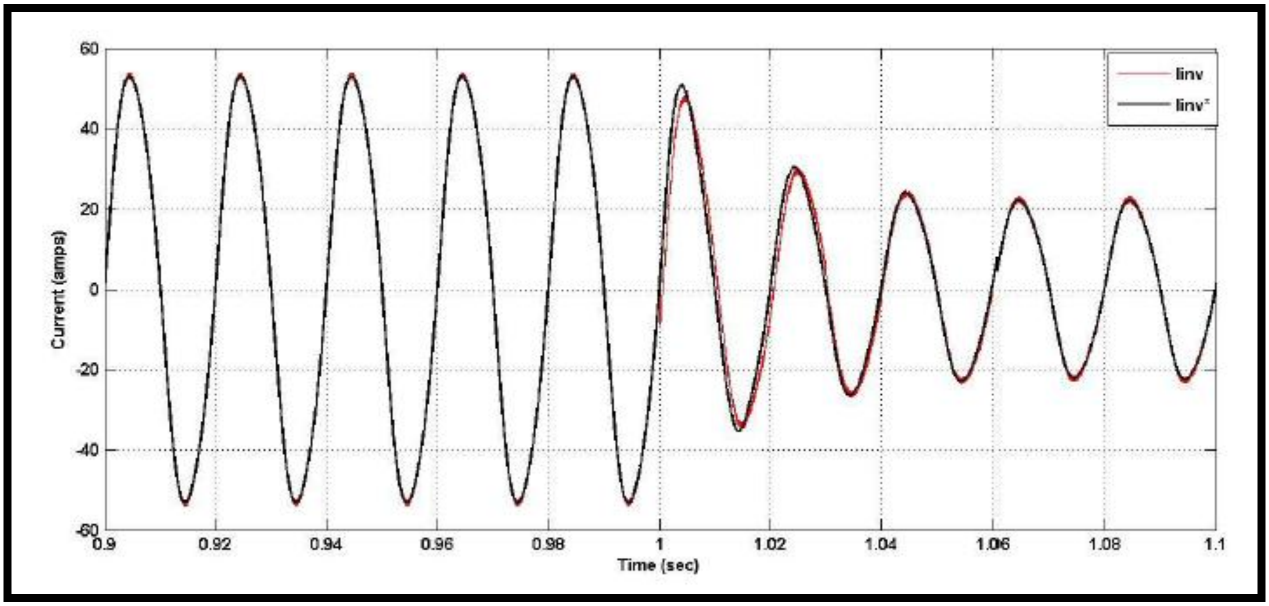


Figure 8.20 Tracking Response of Conventional PI Controller

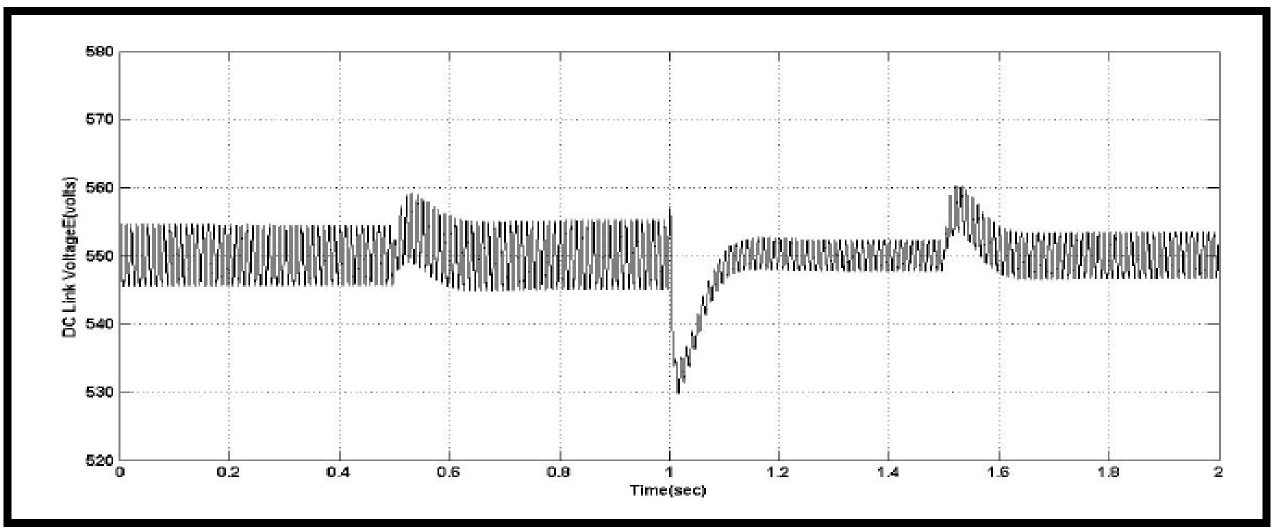


Figure 8.21 DC link Voltage

In this part the simulation result of second stage has been examined. The proposed nonlinear current controller for single phase VSI has to ensure proper tracking of reference inverter output current i_{inv}^* . Fig. 8.18 shows i_{inv}^* and i_{inv} over the entire period of simulation. For better viewing, the tracking response has been magnified at $t = 1\ sec$ and magnified response has been shown in fig. 8.19 and Fig 8.20 shows the tracking response of conventional PI controller during these transient in environmental condition. From fig. 8.19 and fig. 8.20, it is evident that the proposednonlinear controller has a good tracking response during large input transients as well.

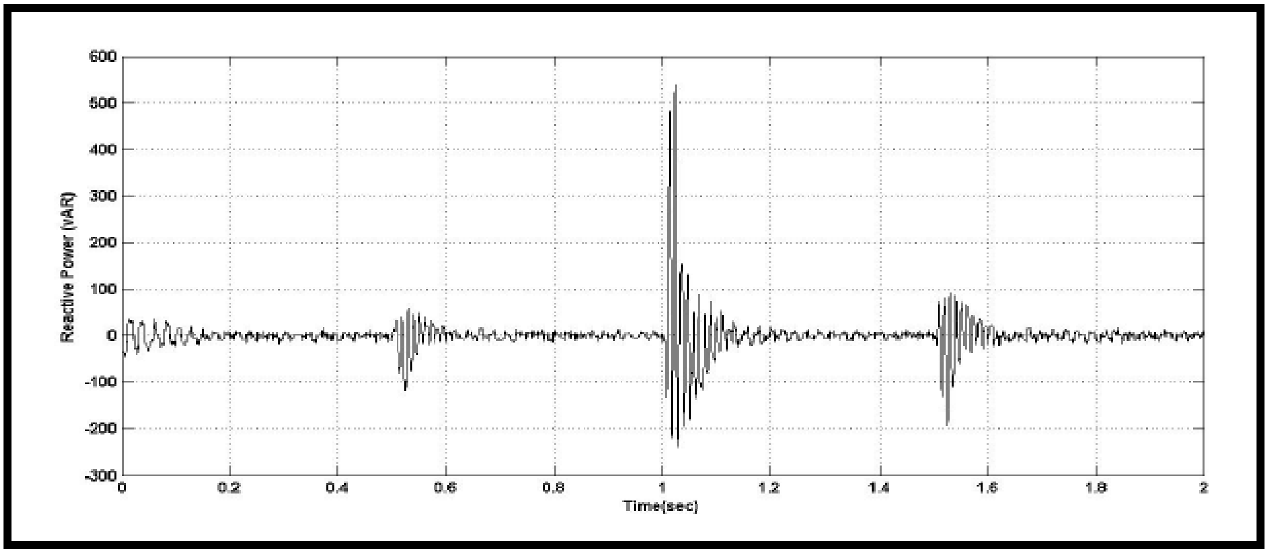


Figure 8.22 Reactive Power Supplied By VSI

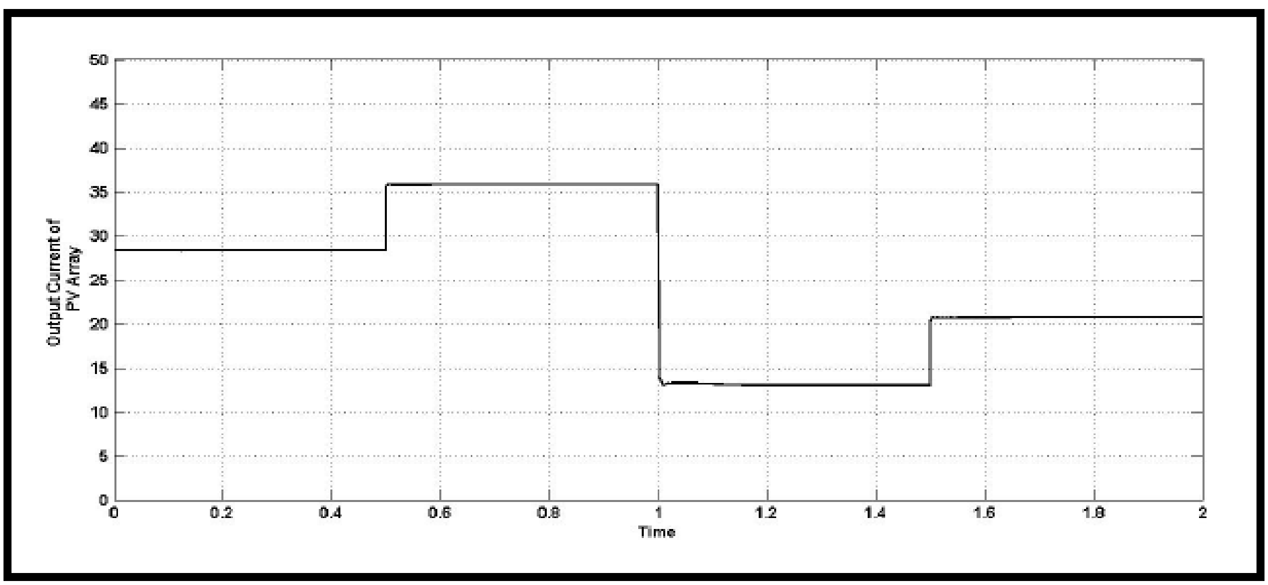


Figure 8.23 Output Current of PV Array

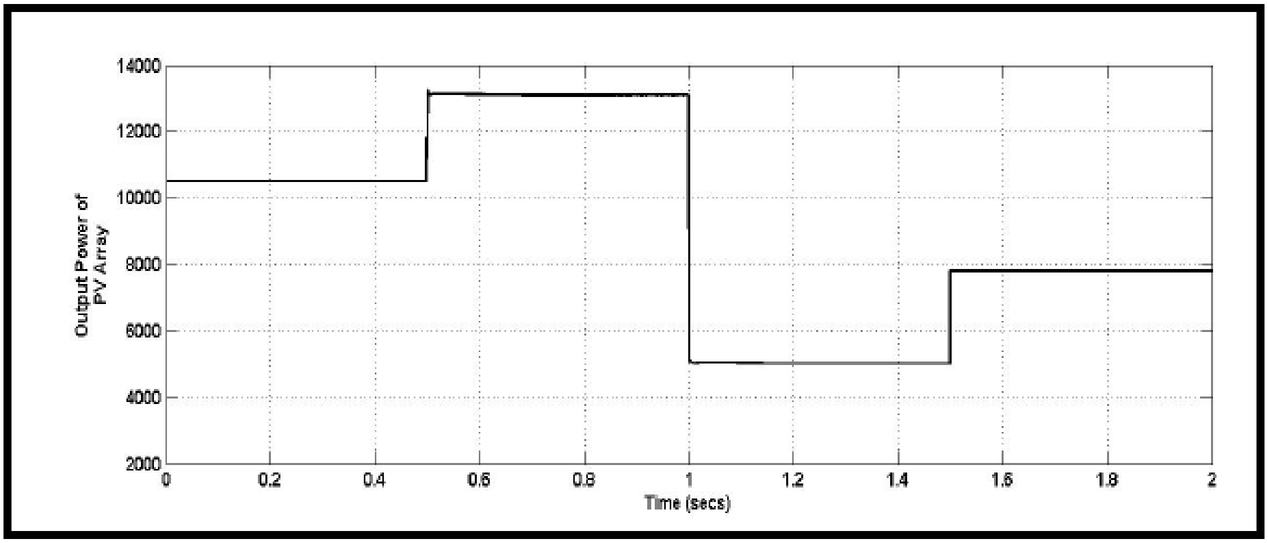


Figure 8.24 Output Power of PV Array

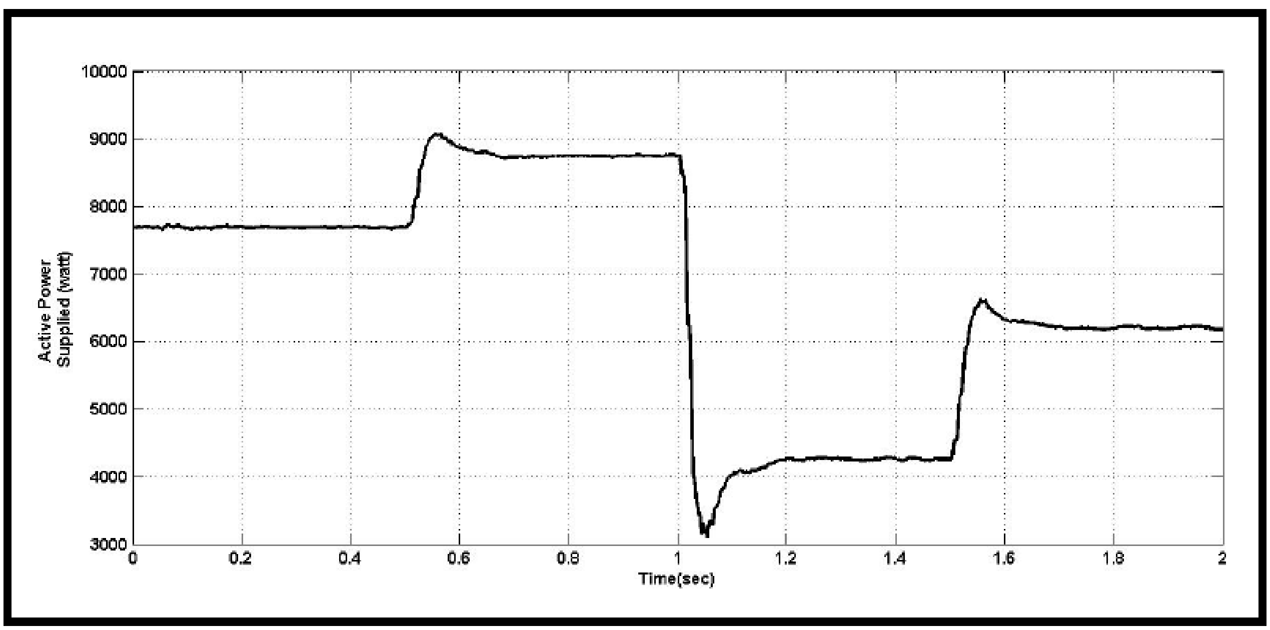


Figure 8.25 Active Power Supplied by VSI

The internal state must be stable for any change in environmental condition. Stability of DC link voltage can be verified from fig. 8.21. The simulation result shows that the DC link voltage has been maintained at 550v, when the system is subjected to rapid changes in the environmental conditions. As discussed earlier the there exists a ripple of frequency $2\omega_0$ in the DC link voltage .The convergence of reactive power supplied by the VSI to zero, with few initial oscillation is evident from fig. 8.22. The output current and output power of PV array has been shown in fig.8.23 and fig. 8.24 respectively. This shows a satisfactory operation of PV array over the entire range of operating points. The active power supplied by VSI is directly proportional to available solar radiation and has been shown in fig. 8.25.

8.4 Three phase H bridge Inverter

MATLAB simulink model of system has developed. Under varying temperature conditions Solar PV module develops variable DC voltage, this voltage is given to feed the closed loop voltage Mode Controlled DC-DC Boost converter. This output , which comes from boost converter is constant voltage and which is acted as source to 5- level H bridge inverter . Output waveforms are showing in following diagrams when we are not connecting MPPT. Figure shows Simulink model of 3-phase system with single phase inverter. Figure shows the output voltage of inverter as well as across load terminals. The FFT analysis is also mentioned below to prove THD.

In order to get THD level of the waveform , a fast fourier transform (FFT) is applied to obtain the spectrum of the output current and output line voltage as shown in figures . The THD of the output voltage of five-level H Bridge inverter is 3.32 % and THD of output load line current of five-level H bridge inverter is 3.29 %.

8.4.1 Simulation of 3-phase H Bridge Inverter with DC source

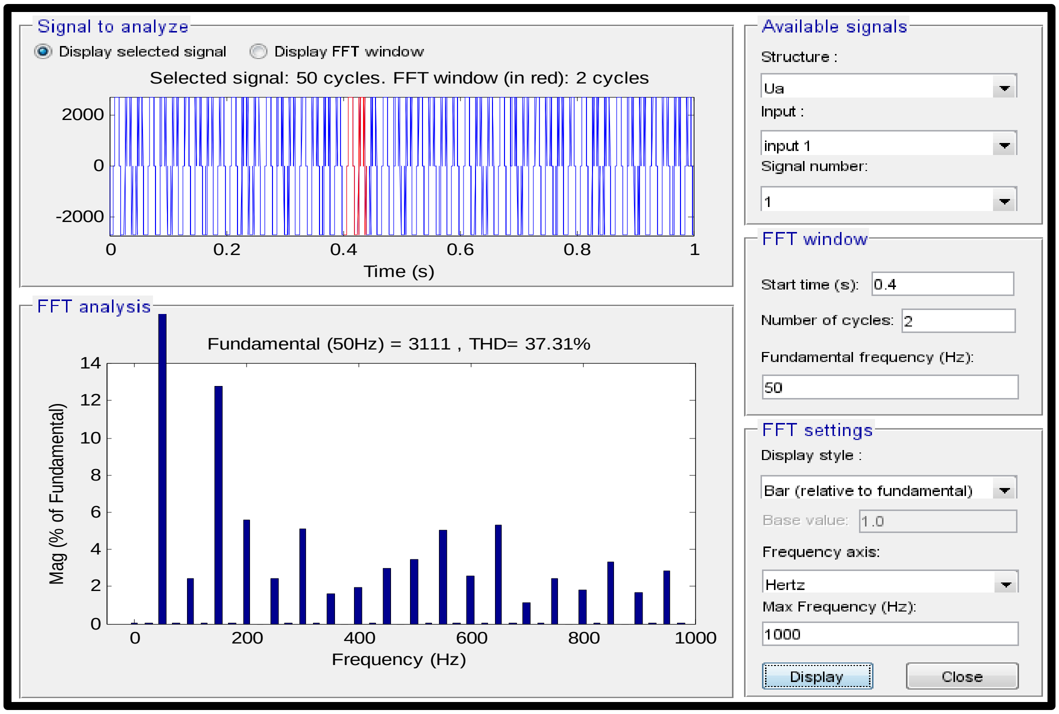


Figure 8.26 THD analysis of phase voltage at CHMLI Terminal

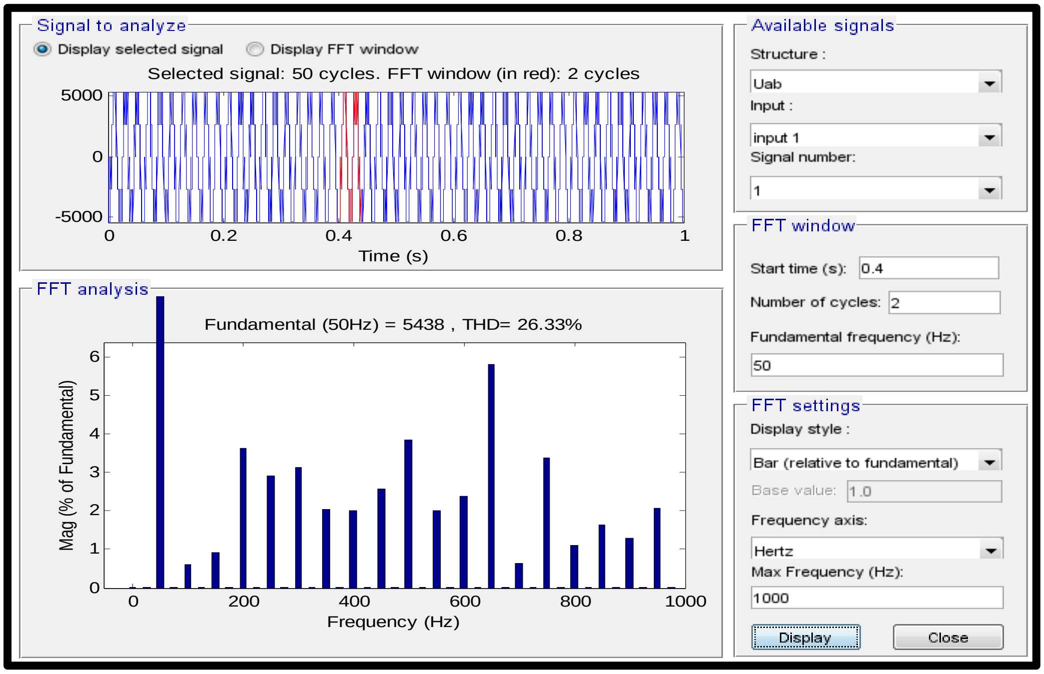


Figure 8.27 THD analysis of line to line voltage at CHMLI terminals

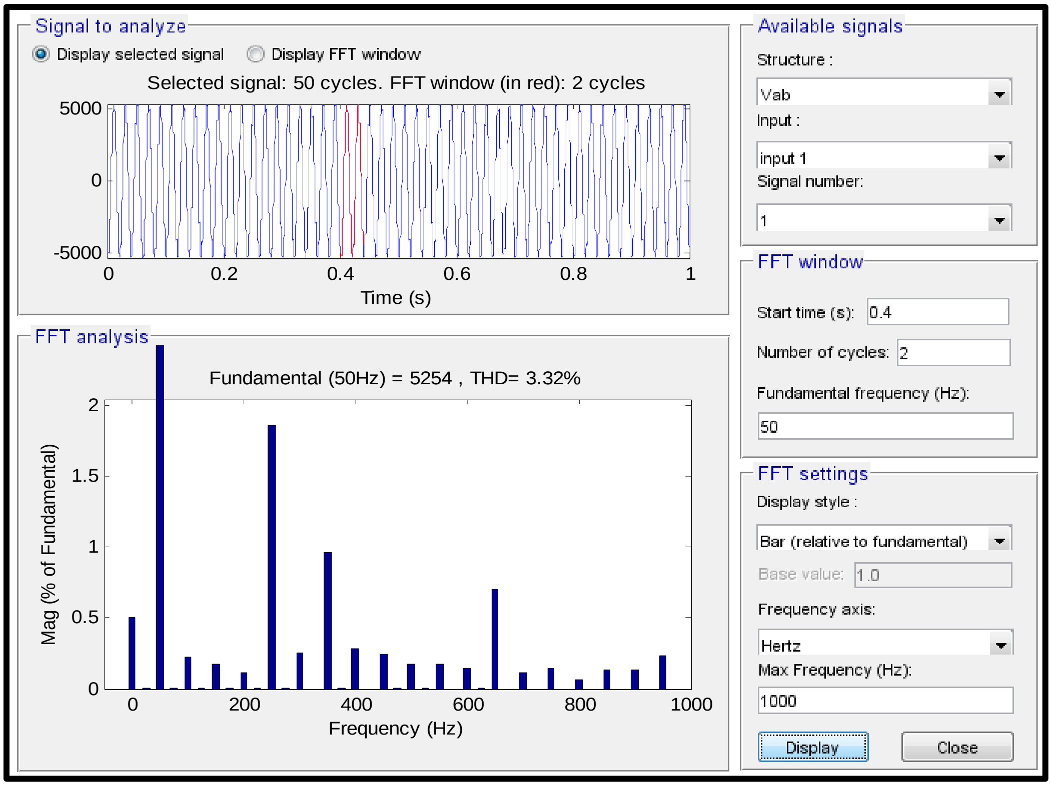


Figure 8.28 THD analysis of line to line voltage load terminals

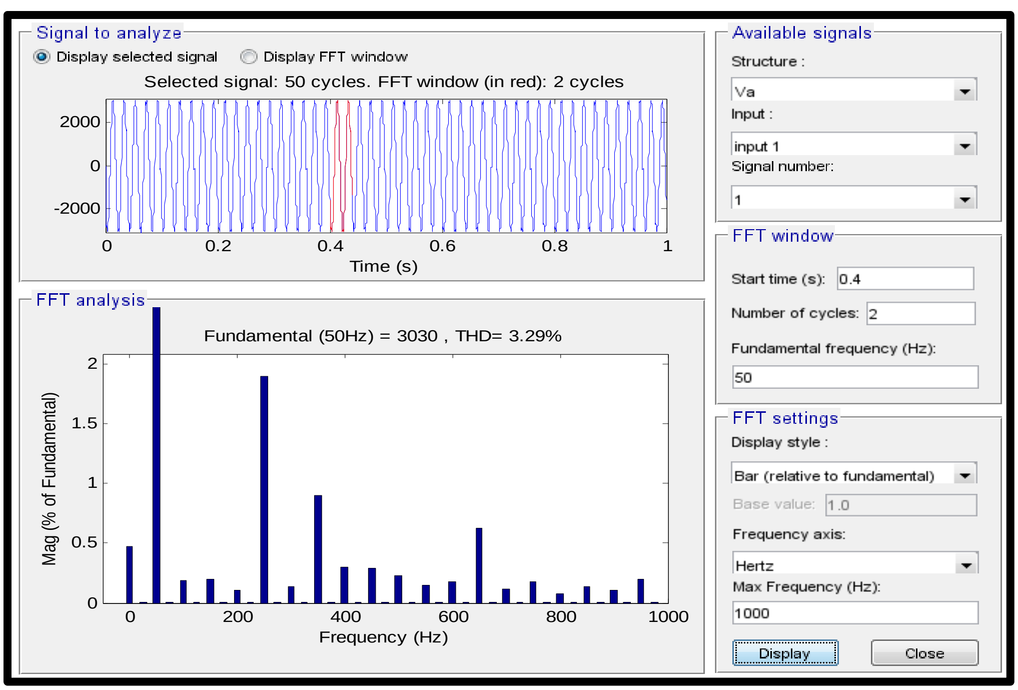


Figure 8.29 THD analysis of phase voltage at load terminals

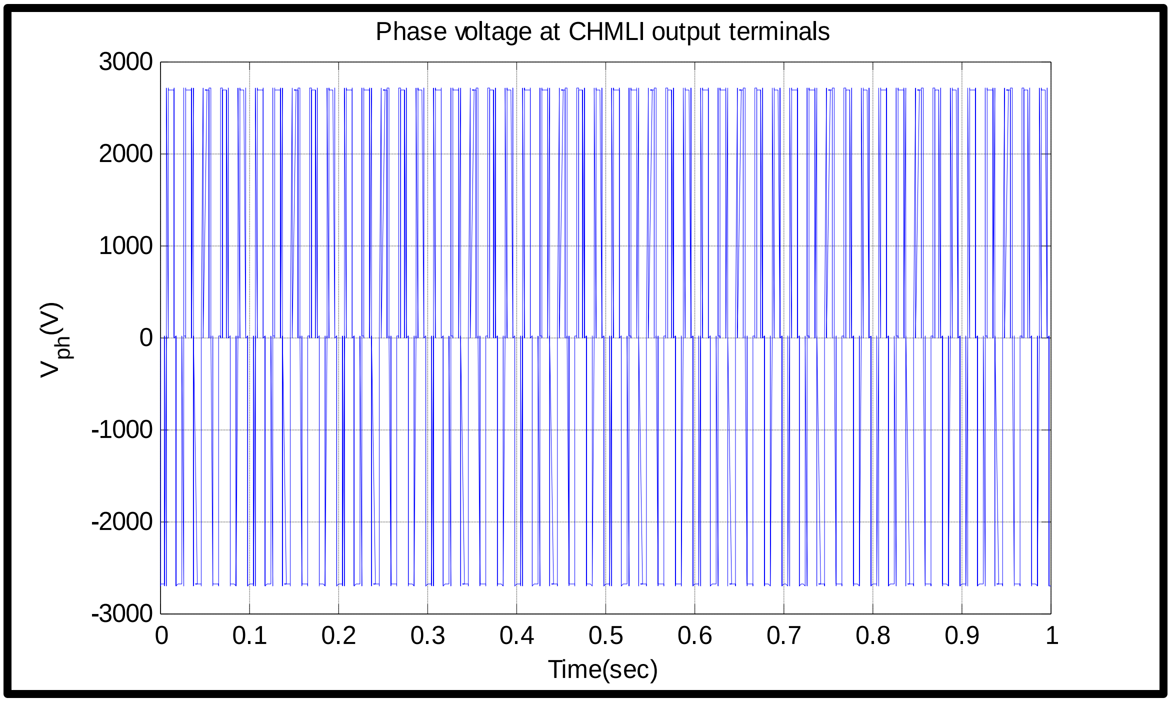


Figure 8.30 phase voltage at CHMLI output terminals

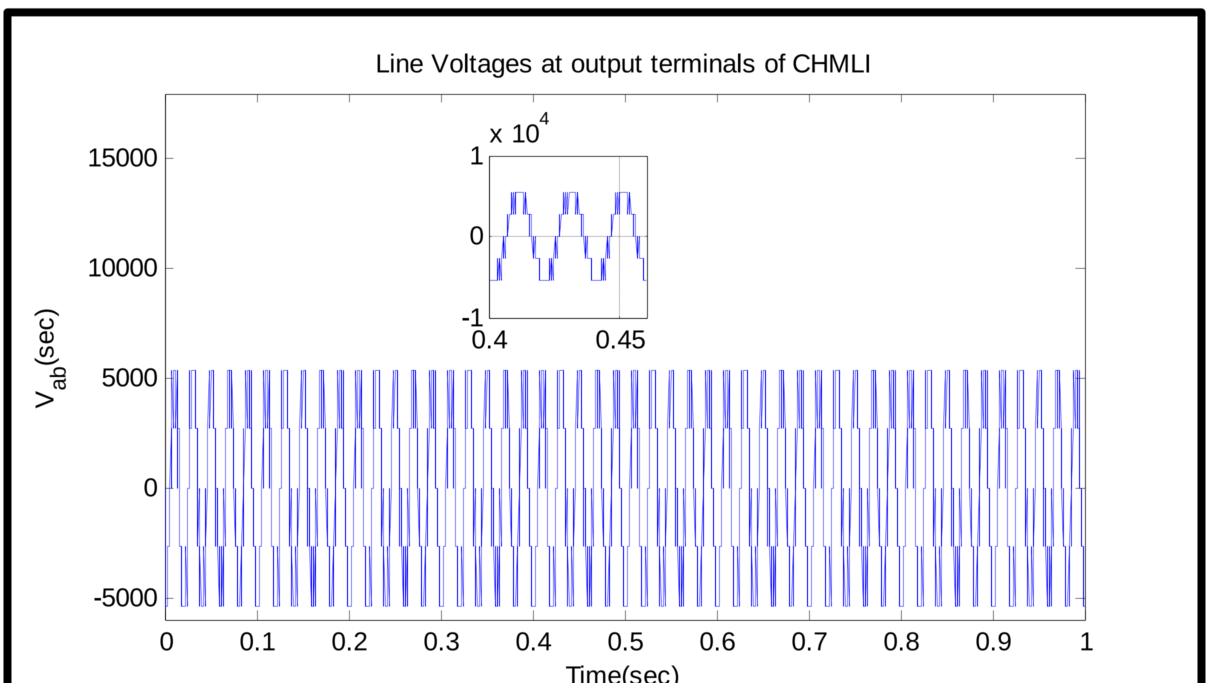


Figure 8.22: line to line voltage at CHMLI terminals

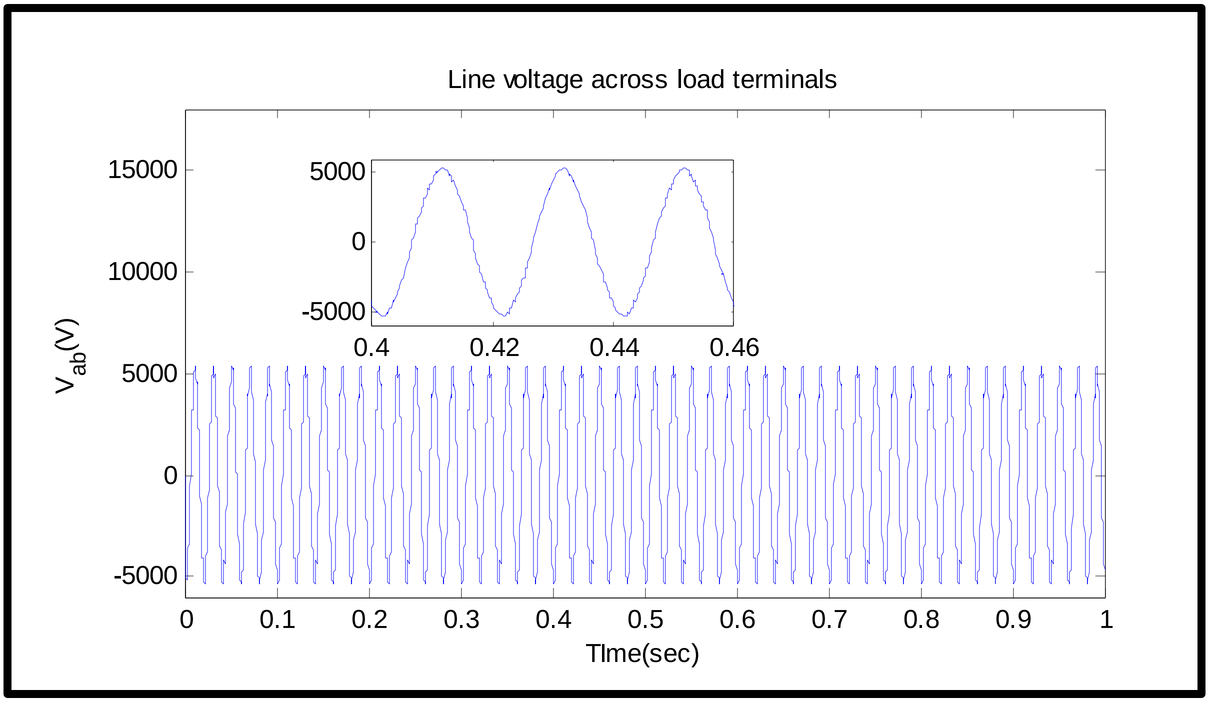


Figure 8.31 line to line voltage across load terminals

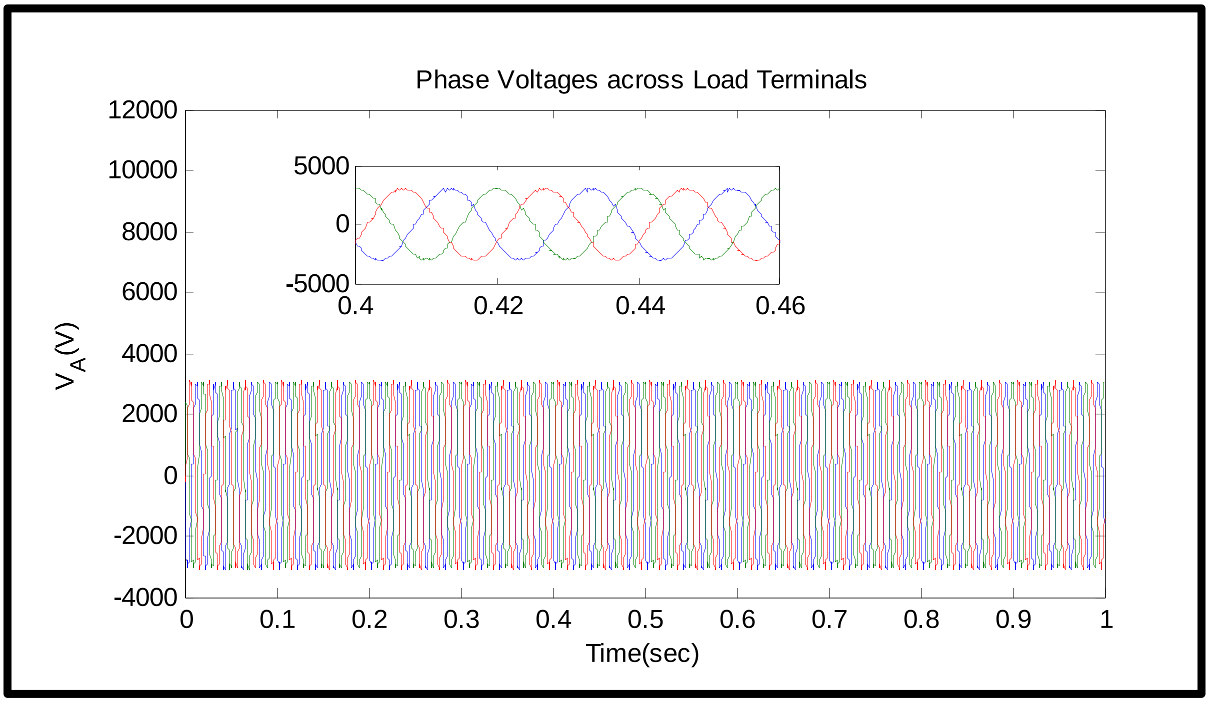


Figure 8.24: Phase voltage across load terminals

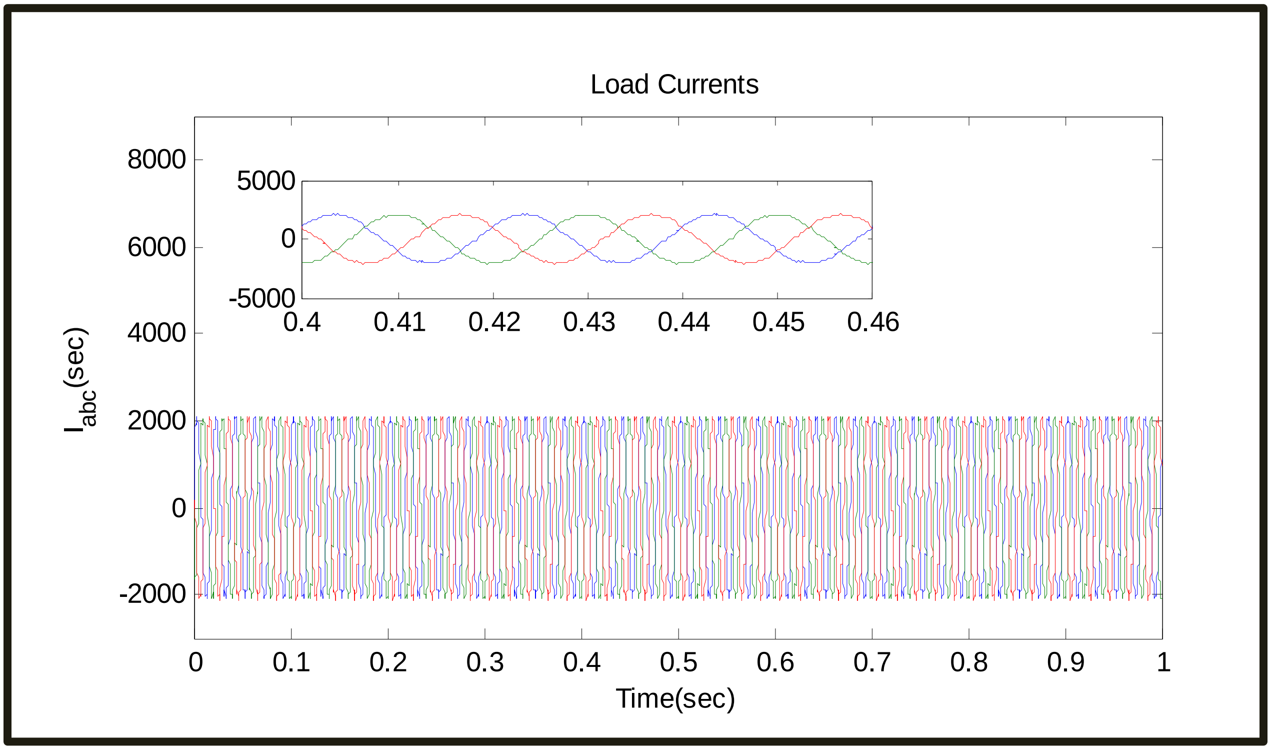


Figure 8.32 Phase current across load terminal

8.4.2 Closed Loop Simulation of 3-phase H Bridge Inverter with solar panel

Power extraction from each string can be same if all strings have same environmental conditions, otherwise the power outputs varies with different environmental conditions among the strings, which leads to unbalanced load/grid currents at PCC. Simulation results for both cases have been presented in following subsections. In both cases, incremental conductance maximum power point technique is employed to track maximum power from each string.

1. **Load sharing during even string powers:** This case is possible only when all the strings have same irradiations and temperature. Power extracted from each string is shown in Figure . From this figure, it clearly observed that all strings are able to operate at maximum power point conditions of almost same value. In addition, the results also reveal that to reach the steady state operation, it takes 4secs. Once it reached to steady state, voltages and currents are extracted with designed regulations (5% for both voltage and current), which can be seen from the zoomed view of corresponding waveforms of Figure .

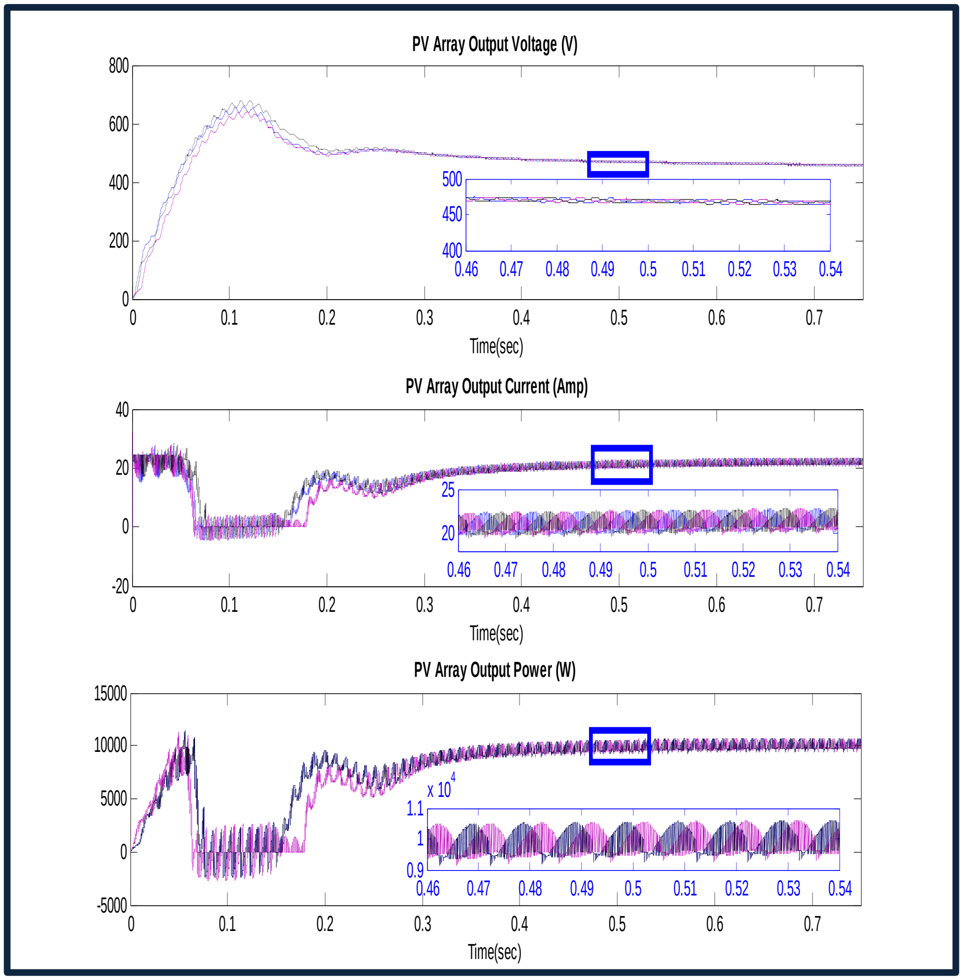


Figure 8.33 String output (a) voltage (b) current and (c) power

To achieve the parameter functions such as MPPT tracking, inversion, synchronization, and active and reactive power control, the required modulation wave is shown in figure 8.34. With this modulating wave which is obtained through the control scheme (MPPT, DC bus regulation, Current Controller and Voltage feed forward compensation) along with SVPWM mentioned in the above section, MPP is tracking perfectly and proving 438.36V and 10.152KW from each string.

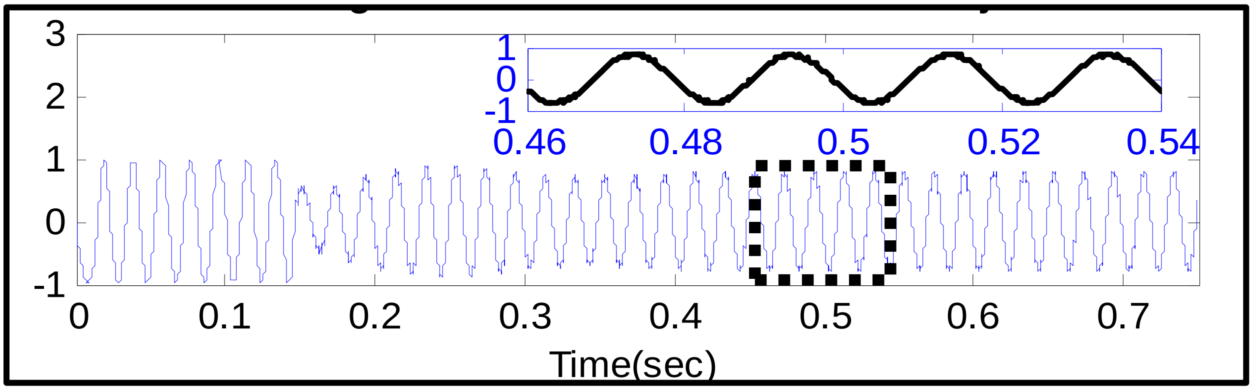


Figure 8.34: modulating wave

The powers coming from each string is given to each bridge of 3-level MMC, is converted into AC and its phase voltages are shown in Fig.8.35 (a). This MMC is connected to PCC through a coupling inductor of 5mH with the equivalent series resistance of 0.02Ω. The voltages available at PCC are shown in Fig.8.35 (b). From this figure, it can be realized that the voltage is able to maintain constant (326V) all the time before/after applying the load change took place at 0.5sec.

The currents coming from MMC and flowing through coupling inductor and PCC are same as shown in Fig. 8.35 (c). It reveals that currents are able to maintained constant magnitude (61.04A peak) as input power is constant because there is no change in applied irradiation and temperature (change in temperature/irradiation is considered and explained in next section). As 50% of load change is applied at 0.5sec, which varies from 20KW to 10KW, current drawn by load is 41A till 0.5s and 20.5A after 0.5s.

The excess current remaining after fed to local load is fed to grid i.e. 20A till 0.5s and 40A after 0.5s at 100W/m^2 and 298^oK. The results of load and grid currents are shown in Fig. 8.35 (d) and 8.35 (e) respectively.

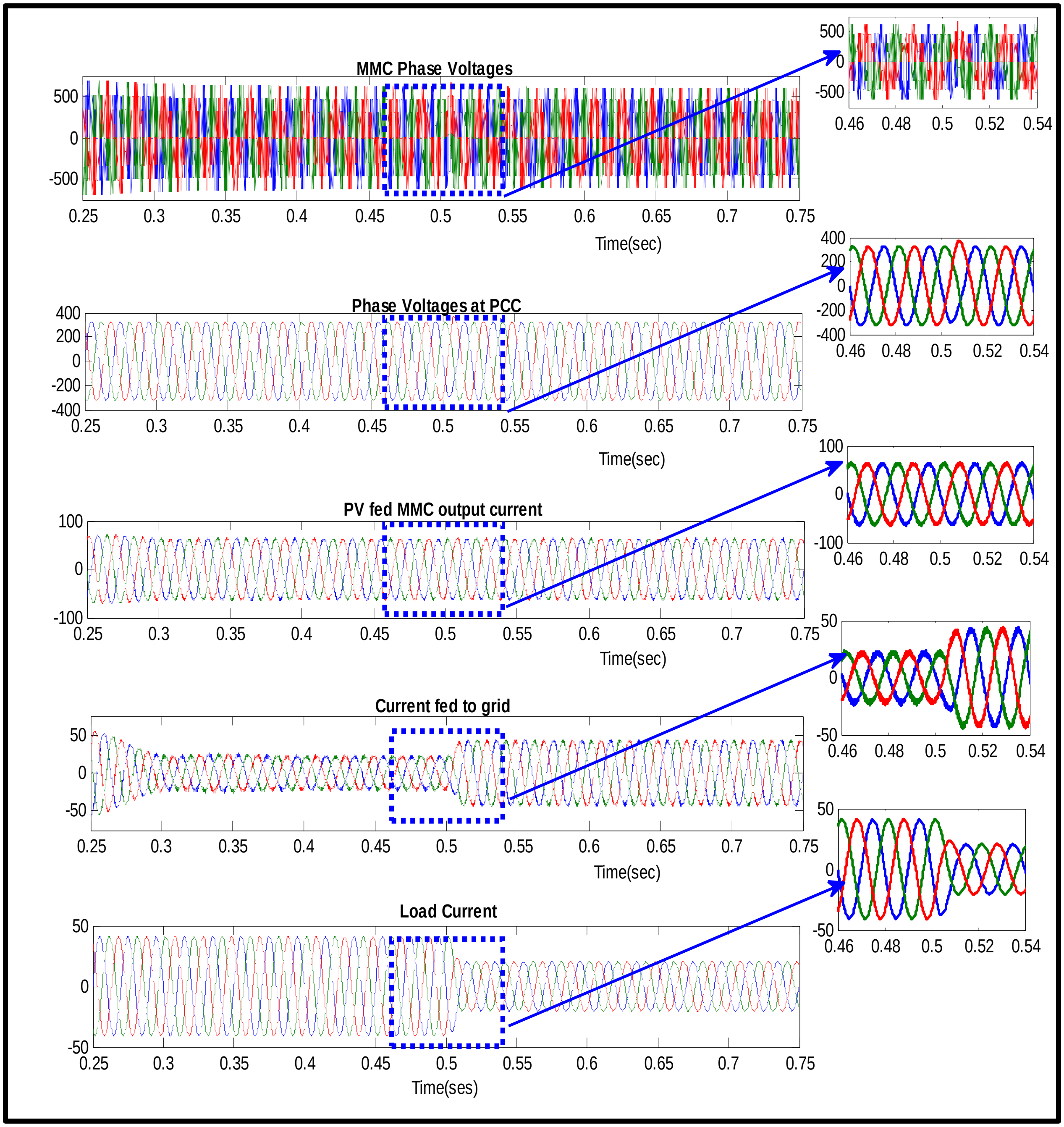


Figure 8.35 parameters after inversion (a) MMC Phase Voltages (b)Voltages at PCC (c)inverter currents (d) Currents fed to grid (e) currents fed to local load

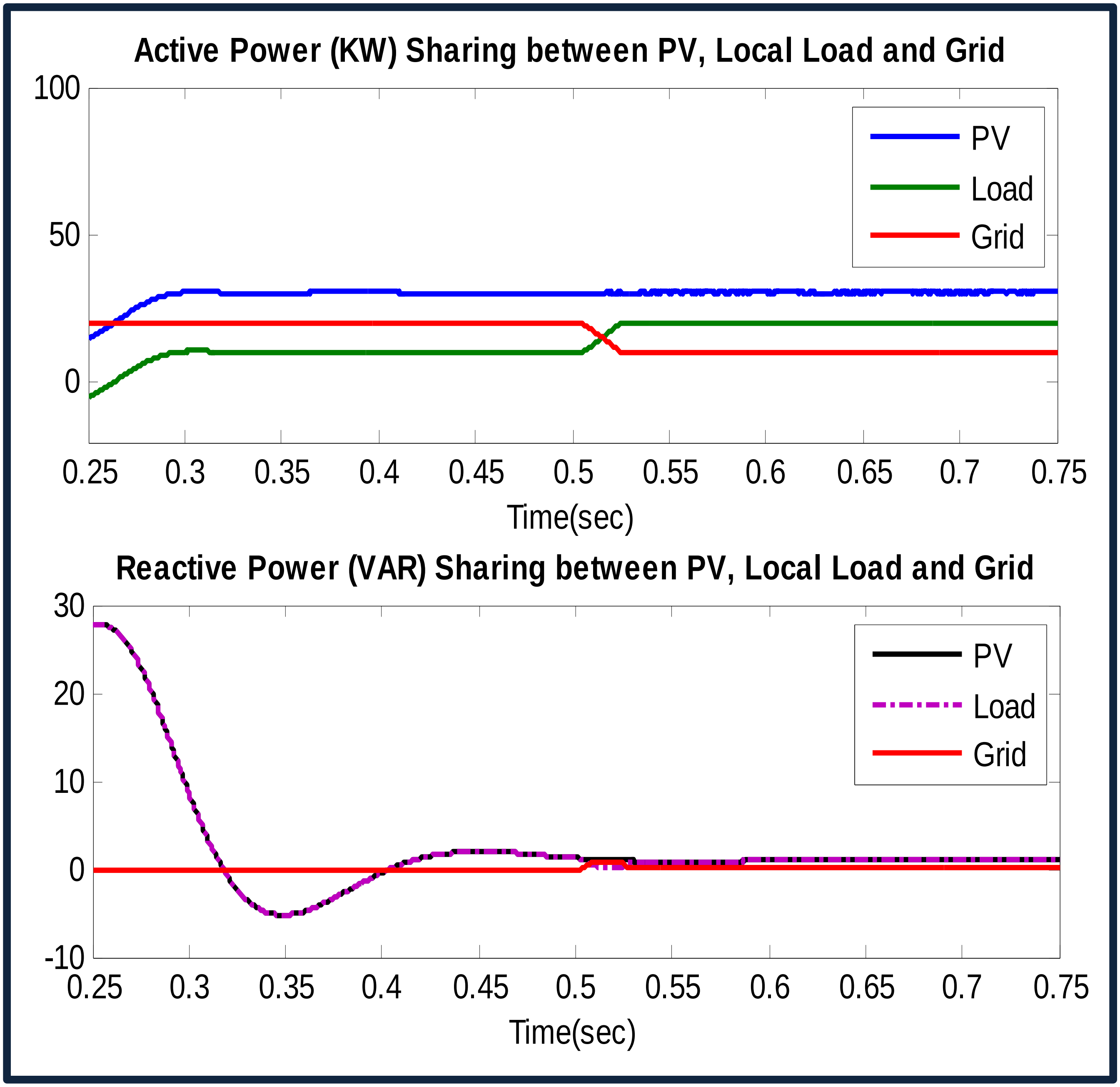


Figure 8.36Active Power and Reactive Power sharing between PV, Local Load and Grid

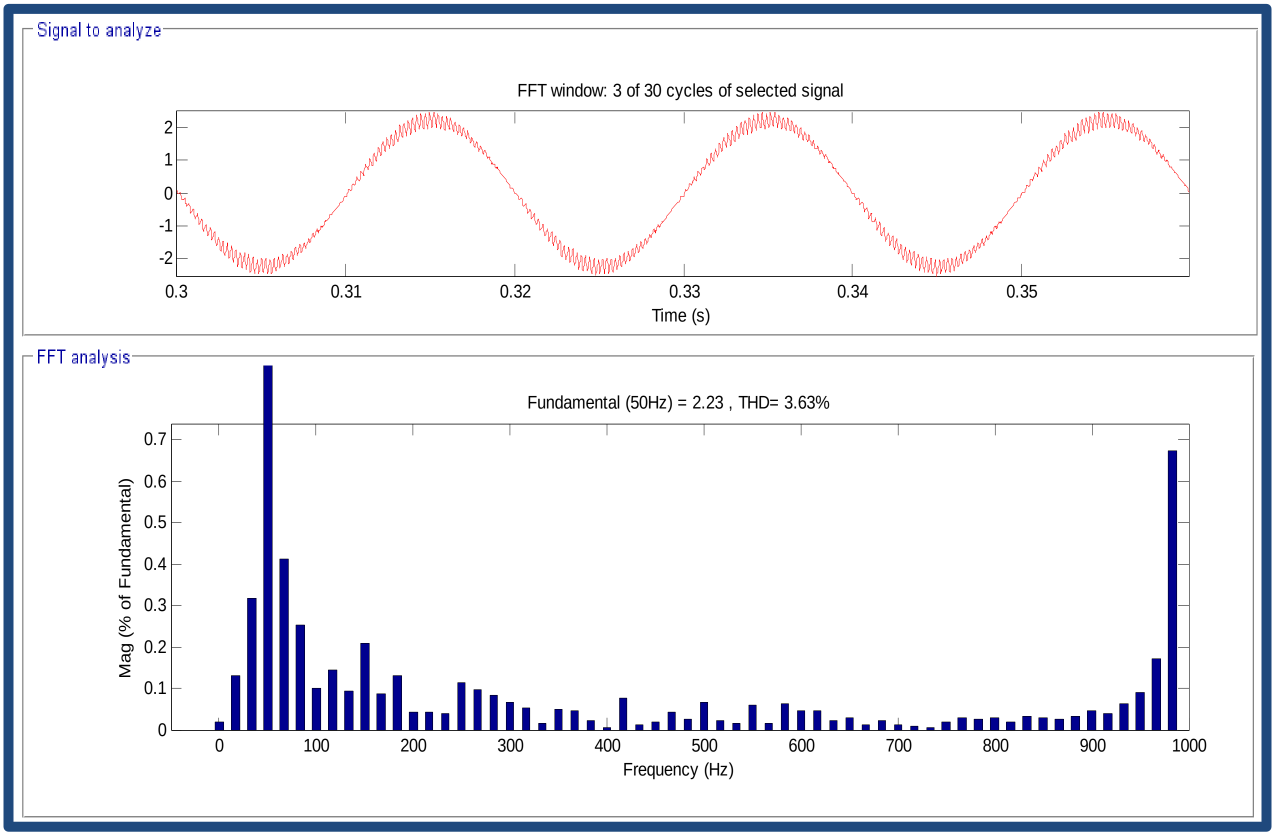


Figure 8.37 THD analysis of Grid current

8.5 Conclusion

In this chapter simulation for single phase and three phase has done with DC source and PV as a source and result has been carried out. This chapter gives the THD value which is controlled by proposed control scheme and active power control is also there that is to maintain unity power factor.

CHAPTER 9

SYSTEM HARDWARE DEVELOPMENT

9.1 Development of system hardware

System Hardware is developed mainly in three stages:-

- development of power circuit
- measurement of system parameters
- development of control

9.2 Power circuit Development

9.2.1 Power circuit:

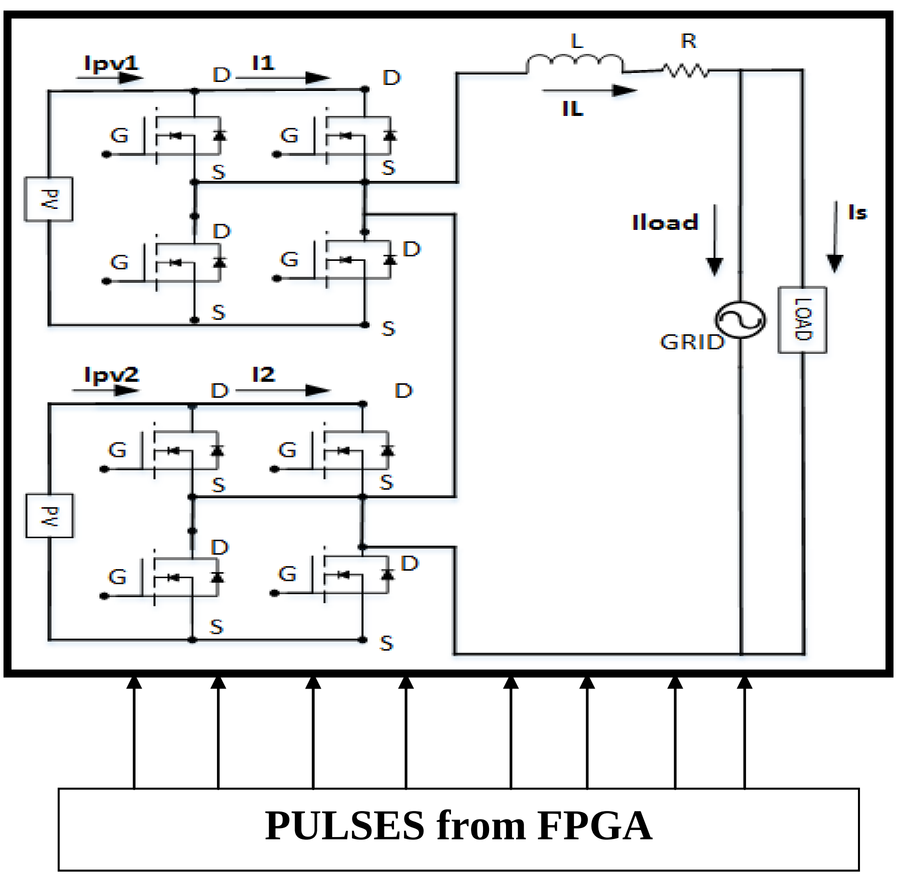


Figure 9.1 Power circuit of single phase 5-level H bridge Inverter

Figure 9.1 shows the power circuit of a single phase H Bridge inverter.

Six self commutated semiconductor switches (S1 to S6) with anti parallel diodes (D1 to D6) are used in PWM converter. The switches need not have a reverse blocking capability. They may be realized using power transistors, MOSFETs and IGBTs based on the rating of the APF. Fast recovery diodes should be used for diodes D1 to D6 . MOSFETs IRF 460,(20A,500v at 20^0C), with built-in fast recovery diodes are used as switching devices, due to its easy availability at low cost. To ensure proper heat dissipation and protection, a suitably designed Snubber circuits is connected across each device and are mounted on a suitable heat sink.

Specifications:-

- MOSFET – IRFP 460 (500v, 20A) : 10 nos.
- Drain to source voltage (V_{dss}) = 500v
- Source to drain resistance during on period ($R_{DS(on)}$) = 0.27**Ω**
- Rated drain current (I_D) = 20A

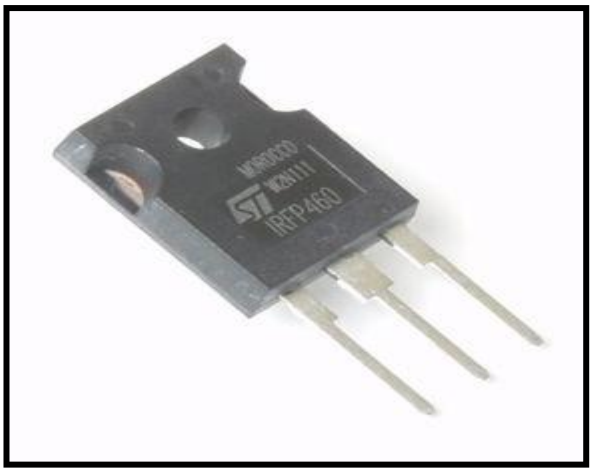


Figure 9.2 MOSFET IRFP460

- Heat Sinks (5” x 2.5” top surface , 5mm sheet thickness): 10 nos.
- Capacitor Rating: 2200µF, 250v
- Inductor 700µH, Ferrite Core

Each MOSFET switch consists of an inbuilt anti-parallel freewheeling diode. No forced commutation circuits are required for the MOSFET’s because these are self commutated devices (They turn on when the gate signal is high and turn off when the gate signal is low). The load inductance restricts large di/dt through MOSFETS ; hence turn off snubber is required for protection. RCD (resistor, Capacitor and Diode) turn off circuit is connected to protect the switch against high dv/dt and is protected against power voltage by connecting MOV (Metal Oxide Varistor). Fast recovery diodes are connected in series with each switch and are specifically required for this project. They eliminate the possibility of flow of reverse current when switches are on. As the switching frequency is high her, the recovery of diodes must also be fast.

9.2.2 Snubber Circuit (Protection of MOSFETS)

Since power handled by the prototype circuit is less (up to 10A), RC snubber circuit has been used for protection of main switching device. Switching high current in short time gives rise to voltage transients that could exceed the rating of the MOSFET. Snubbers are therefore needed to protect the switch from transients. Snubber circuit for MOSFET is shown in figure 8.3.The diode prevents the discharging of the capacitor via the switching device, which could damage the device due to large discharge current. An additional protective metal oxide varistor (MOV) is used across each device to protect against over voltage across the device.

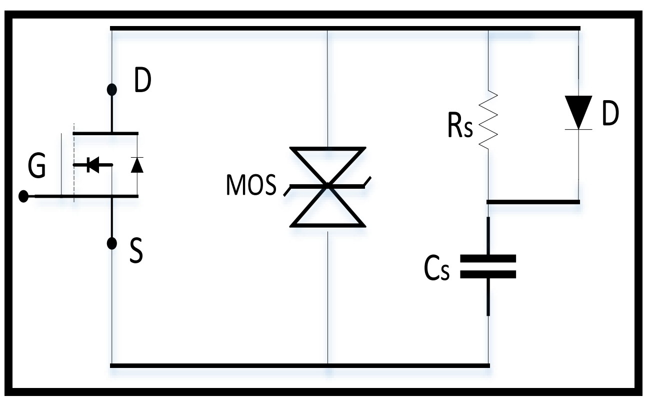


Figure 9.3 Snubber circuit for MOSFET protection

<u>Components</u>

- Snubber circuits: 10nos
- Capacitance : 0.1µF,1000v
- MOV (Metal oxide Varistor): 320v
- Diode- IN5408

- Capacitor,C = 0.1µF
- Resistor R= 0.1kΩ,5w

9.3 Pulse amplification and isolation circuit

The pulse amplification circuit for MOSFET is shown in figure 8.4.The opto coupler MCT-2E provides necessary isolation between the low voltage isolation circuit and high voltage power circuit. The pulse amplification circuit is provided by the output amplifier transistor 2N2222. When the input gating is +5v level, the transistor saturates , the LED conducts and the light emitted by it falls on the base of the phototransistor, thus forming its base drive. The output transistor thus receives no base drive and remains in the cut-off state and a +12v pulse (amplified) appears at its collector terminal.

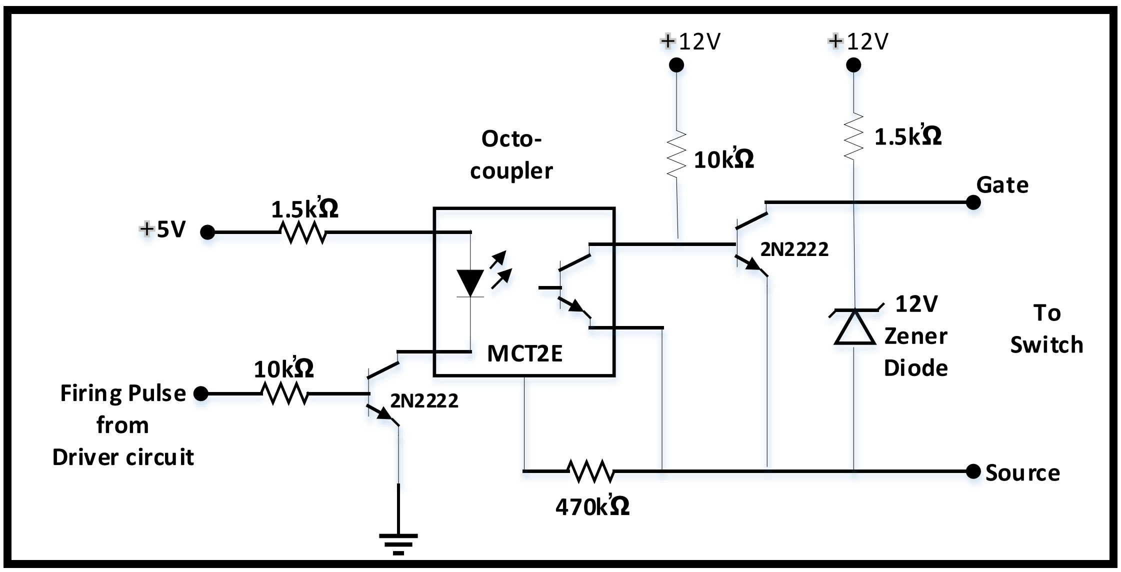


Figure 9.4 Pulse Amplification and Isolation Circuit

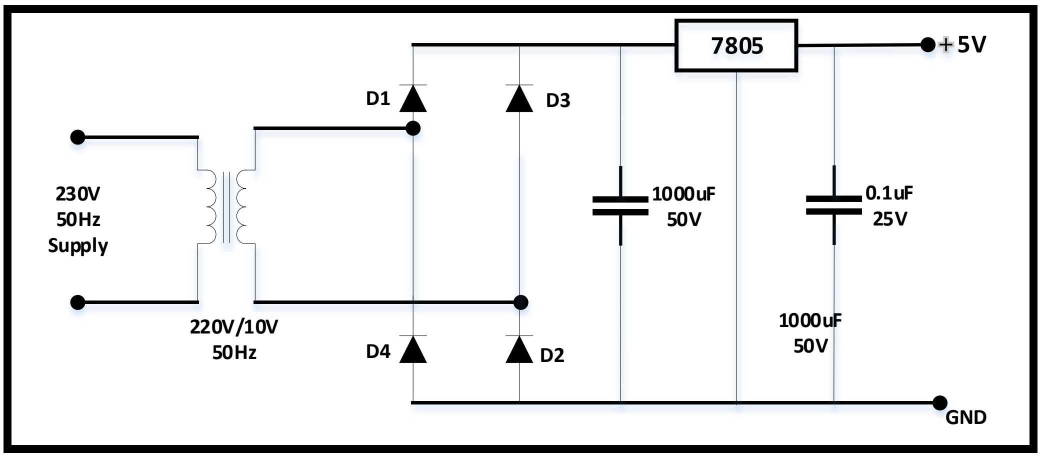
When the pulse reaches ground level, the input switching transistor goes to cut-off state and LED remains off, thus emitting no light and therefore the photo–transistor remains off. The output transistor receives base drive and saturates, hence the output falls to ground level. Therefore, the circuit provides proper amplification and isolation.

Further, since slightest above 20v can damage the MOSFET, a 12v Zener diode is connected across the output isolation circuit . This clamps the triggering voltage to 12v.

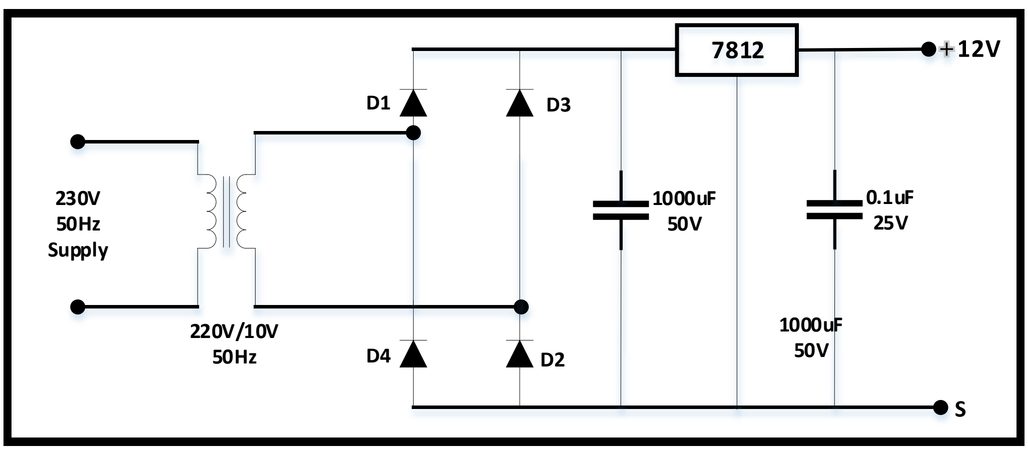
9.4 Power supplies

DC regulated supplies (+12v ground +12v,+5v) are required for providing biasing to various circuits like pulse amplification and isolation circuits , Hysteresis controller and voltage detectors etc. Using IC,s 7812 for +12v, IC 7912 for -12v and 7805 for +5v.

The circuit diagram of the power supplies is as shown in following figures.



(a)



(b)

Figure 9.5 Connection diagram for power supplies

(a) +5v (b)+12v

9.5 MEASUREMENT OF SYSTEM PARAMETERS

For accurate effective and reliable operation of a system in closed loop measurement of various system parameter and their conditioning is required, which must meet the following requirements-

- high accuracy
- galvanic isolation between high and low voltage side,
- ease of installation
- linearity and fast response, etc.

These requirements are fulfilled to a great extent, with the availability of Hall Effect current and voltage sensors. These sensors are now available in variety of rating and range to meet the system requirements. In order to implement the control algorithm following signals are to be sensed

- AC source currents are required for processing in PWM controller with estimated reference currents for the generation of switching signals,
- DC link voltage is required for PI processing to estimate the active component of current.

9.5.1 AC CURRENT SENSING

Ac source currents are sensed using PCB mounted Hall Effect current sensors (HTP 50). These current sensors provide galvanic isolation between the low voltage control circuit and high voltage power circuit and require a nominal supply voltage of the ±12v to ±15v. It has the transformation ratio of 1000:1; hence to obtain the desired value to meet the control requirements, its output is scaled properly.

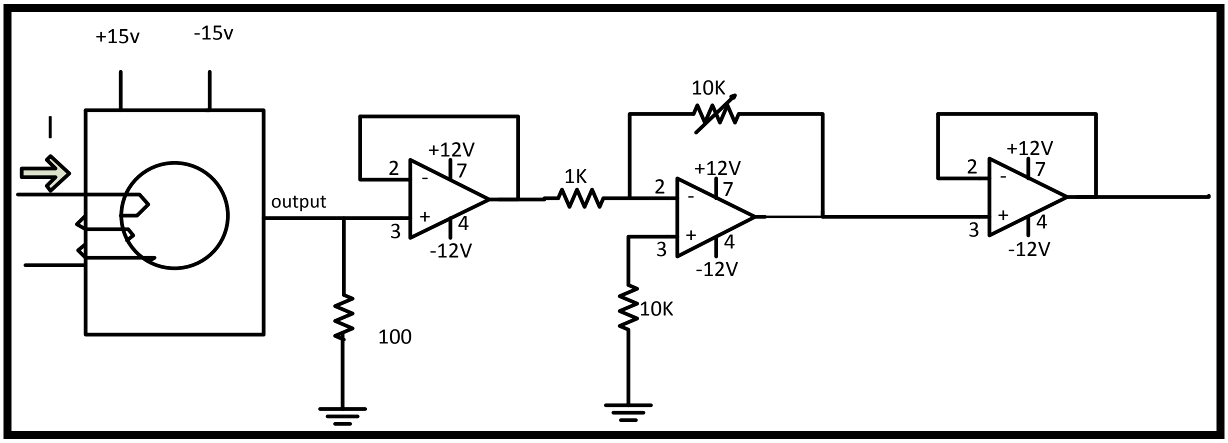


Figure 9.6 AC current sensor circuit

9.5.2 AC VOLTAGE SENSING

AC voltage sensors are required to sense PV voltage as well as grid voltage. Only sensing two voltage are sufficient for three phase three wire system, but all the three voltages are sensed to avoid the delay introduced due to the subtraction circuit. The circuit diagram of the sensing ac voltage is shown in the figure. To scale down the voltage within the range of AD202 (isolation amplifier) resistors are used .

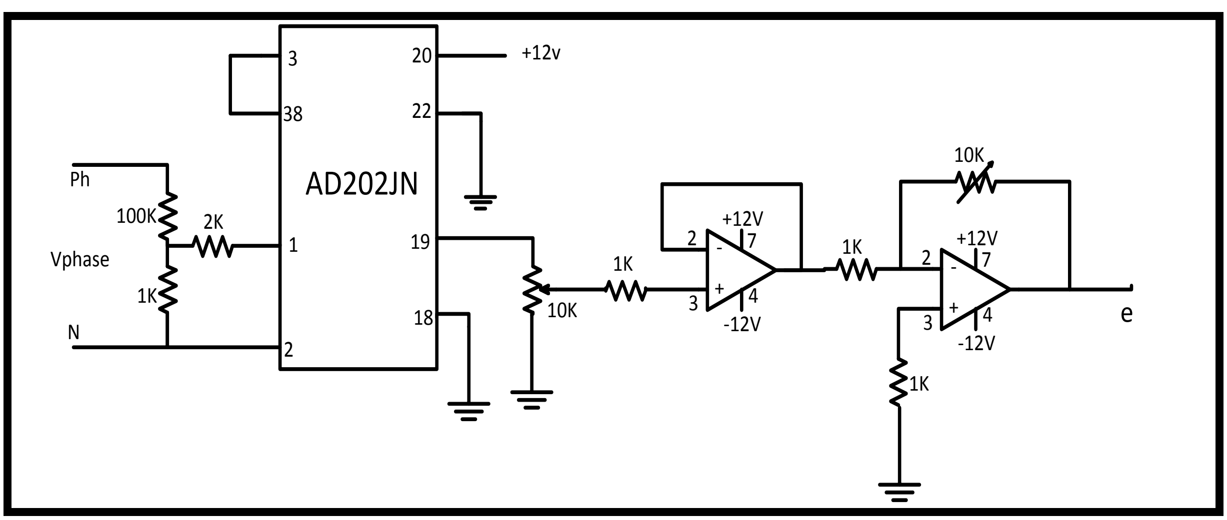


Figure 9.7 AC voltage sensing circuit

Op-amp circuits are used at the output of AD202 for scaling.

9.6 Hardware Results

Single phase Open loop H bridge 5 level inverter

Hardware setup and result of open loop 5-level H bridge multi level Inverter is shown in following figure 9.8 to 9.10

Figure 9.8: Hardware setup of 5-level H bridge inverter (open loop)

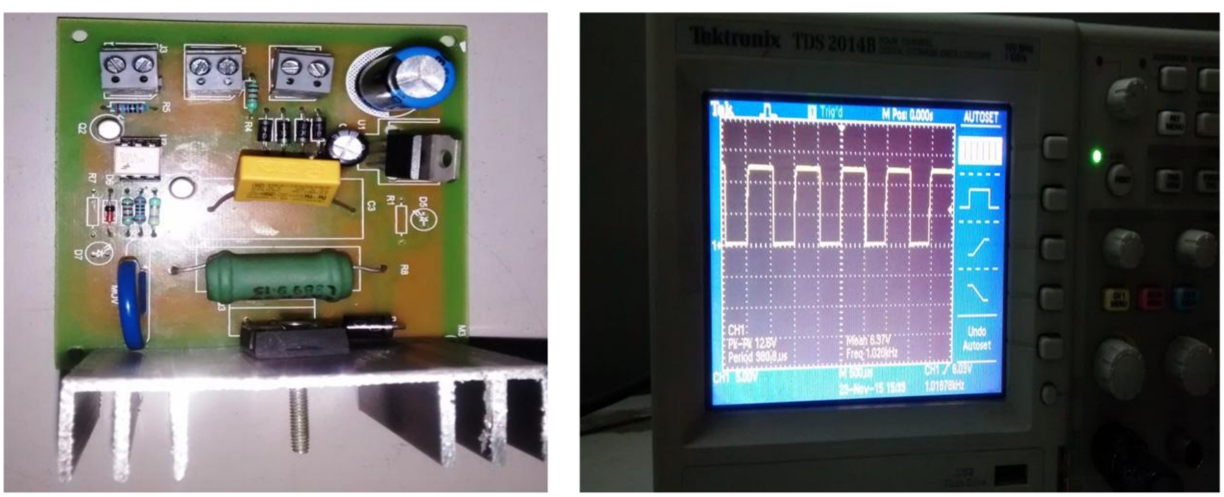


Figure 9.9 : Driver circuit and its output pulses

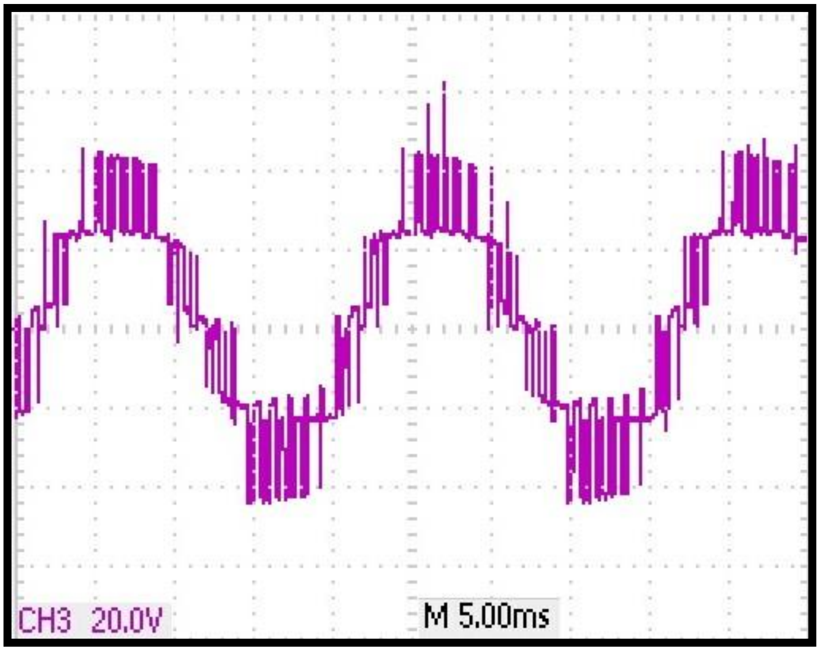


Figure 9.10: Output Line voltage of 5-level H bridge Inverter

FPGA pulses, Hardware circuits of voltage sensor, current sensor, Boost converter and dead band circuit are shown in appendix D.

9.7 Conclusion

In this chapter the various components developed for the hradware implementation are discussed. The various circuits of power, measurement and control circuitry are shown. The experimental results of this developed prototype are shown and discussed in this chapter.

Chapter 10

CONCLUSIONS AND FUTURE SCOPE

In this thesis to improve the overall efficiency of the grid connected PV system as well as to reduce the PV inverter cost cascaded multilevel inverter topology is used.

The grid-connected PV inverter topologies are also discussed. Inverter topologies depend upon the number of power processing stages. These can be categorized as single stage inverters and dual stage inverters. Many single and dual stage inverter topologies have been reviewed. Among both the topologies single stage inverter is good because it is highly reliable, efficient and less expensive. But there is a problem of transient stability and it must have to handle the entire task itself.

According to the different configurations of the PV system five inverter families can be defined. The DC/AC cascaded inverter is best choice for medium and large PV applications. Other benefit of using this topology is that it can use single stage inverter, which is best from efficiency and cost point of view. Hence, the cascaded H-bridge multilevel inverter can be used as a single stage inverter for cascaded PV systems.

In this thesis firstly the topology discussed for grid connected PV system is single-phase cascaded H-bridge multilevel inverter and further move towards three phase inverter. In addition the issues of PV mismatches addressed. With the help of simulation results it proves that individual MPPT control is necessary to increase the efficiency of system and to reduce the effect of mismatches.

A control scheme for reactive power compensation with independent MPPT control is proposed. In three phase system modulation compensation is used to avoid the power imbalance problem. Simulation and experimental results show that individual MPPT control is achieved to maximize the solar energy extraction of each PV string. The reactive power required by the local load can be provided by the proposed system to realize the power factor correction and reduce distribution losses.

By applying the cascaded H-bridge multilevel inverter topology, the target of $0.10 per watt for PV inverters can be reached. However, this topology increases the volume and labor cost because it requires large number of electrical and mechanical components. The proposed topology keeps many of the cascaded H-bridge multilevel inverter, and has fewer components. The control system design can be simplified by establishing the equivalent model and average model of the proposed PV system.

Simulations of solar PV module, voltage mode control of DC-DC boost converter and cascaded H bridge multilevel inverter are done. FPGA controlled DC-DC boost converter and single phase cascaded H bridge inverter are simulated on Xilinx system generator. Hardware was implemented for boost converter and cascaded H bridge inverter with FPGA control.

The following issues can be considered for possible future work:

1. To improve the efficiency Cascaded inverter topologies are proposed for utility-scale PV systems. In large-scale PV systems, the leakage current of PV modules is a major issue. The leakage current and its suppression in cascaded PV inverters should be studied.
2. The control scheme of the three-phase cascaded VSI is based on balanced input solar power. If PV mismatch happens, the supplied power to the three VSI units would be different.
3. In transformer less PV inverters DC-current injection is of great interest. New control strategies and topologies could be studied, to minimize the DC part in the injected AC current.

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RESEARCH PAPER COMMUNICATED

1. Neha Tak, Dogga Raveendhra, S.P. Singh ,: **FPGA based Solar PV fed Cascaded Multi Level Inverter with self-healing power unbalancing capability, IETE Journal of Research.**

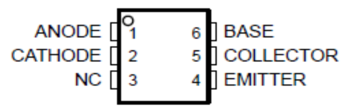
APPENDIX A

Data Sheet for Opto couplers MCT2, MCT2E

COMPATIBLE WITH STANDARD TTL INTEGRATED CIRCUITS

- **Gallium Arsenide Diode Infrared Source Optically Coupled to a Silicon npn Phototransistor**
- **High Direct-Current Transfer Ratio**
- **Base Lead Provided for Conventional Transistor Biasing**
- **High-Voltage Electrical Isolation . . . 1.5-kV, or 3.55-kV Rating**
- **Plastic Dual-In-Line Package**
- **High-Speed Switching:**
  t_r = 5 µs, t_f = 5 µs Typical
- **Designed to be Interchangeable with General Instruments MCT2 and MCT2E**

MCT2 OR MCT2E . . . PACKAGE
(TOP VIEW)



NC – No internal connection

absolute maximum ratings at 25°C free-air temperature (unless otherwise noted)†

Input-to-output voltage: MCT2	± 1.5 kV
MCT2E	± 3.55 kV
Collector-base voltage	70 V
Collector-emitter voltage (see Note 1)	30 V
Emitter-collector voltage	7 V
Emitter-base voltage	7 V
Input-diode reverse voltage	3 V
Input-diode continuous forward current	60 mA
Input-diode peak forward current ($t_w \leq$ 1 ns, PRF $\leq$ 300 Hz)	3 A
Continuous power dissipation at (or below) 25°C free-air temperature:	
Infrared-emitting diode (see Note 2)	200 mW
Phototransistor (see Note 2)	200 mW
Total, infrared-emitting diode plus phototransistor (see Note 3)	250 mW
Operating free-air temperature range, T_A	–55°C to 100°C
Storage temperature range, T_{stg}	–55°C to 150°C
Lead temperature 1,6 mm (1/16 inch) from case for 10 seconds	260°C

† Stresses beyond those listed under “absolute maximum ratings” may cause permanent damage to the device. These are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated under “recommended operating conditions” is not implied. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability.

NOTES: 1. This value applies when the base-emitter diode is open-circulated.
2. Derate linearly to 100 °C free-air temperature at the rate of 2.67 mW/°C.
3. Derate linearly to 100 °C free-air temperature at the rate of 3.33 mW/°C.

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electrical characteristics at 25°C free-air temperature (unless otherwise noted)

PARAMETER			TEST CONDITIONS		MIN	TYP	MAX	UNIT
$V_{(BR)CBO}$	Collector-base breakdown voltage		I_C = 10 µA, I_E = 0, I_F = 0		70			V
$V_{(BR)CEO}$	Collector-emitter breakdown voltage		I_C =1 mA, I_B = 0, I_F = 0		30			V
$V_{(BRECO)}$	Emitter-collector breakdown voltage		I_E = 100 µA, I_B = 0, I_F = 0		7			V
I_R	Input diode static reverse current		V_R = 3 V				10	µA
$I_{C(on)}$	On-state collector current	Phototransistor operation	V_{CE} = 10 V, I_B = 0, I_F = 10 mA		2	5		mA
		Photodiode operation	V_{CB} = 10 V, I_E = 0, I_F = 10 mA			20		µA
$I_{C(off)}$	Off-state collector current	Phototransistor operation	V_{CE} = 10 V, I_B = 0, I_F = 0			1	50	nA
		Photodiode operation	V_{CB} = 10 V, I_E = 0, I_F = 0			0.1	20	nA
H_{FE}	Transistor static forward current transfer ratio		V_{CE} = 5 V, I_C = 100 µA, I_F = 0	MCT2		250		
				MCT2E	100	300		
V_F	Input diode static forward voltage		I_F = 20 mA			1.25	1.5	V
$V_{CE(sat)}$	Collector-emitter saturation voltage		I_C = 2 mA, I_B = 0, I_F = 16 mA			0.25	4	V
r_{IO}	Input-to-output internal resistance		V_{in-out} = ±1.5 kV for MCT2, ±3.55 kV for MCT2E, See Note 4		10^{11}			Ω
C_{io}	Input-to-output capacitance		V_{in-out} = 0, f = 1 MHz, See Note 4			1		pF

NOTE 4: These parameters are measured between both input diode leads shorted together and all the phototransistor leads shorted together.

switching characteristics

PARAMETER			TEST CONDITIONS	MIN	TYP	MAX	UNIT
t_r	Rise time	Phototransistor operation	V_{CC} = 10 V, $I_{C(on)}$ = 2 mA, R_L = 100 Ω, See Test Circuit A of Figure 1		5		µs
t_f	Fall time						
t_r	Rise time	Photodiode operation	V_{CC} = 10 V, $I_{C(on)}$ 20 µA, R_L = 1 kΩ, See Test Circuit B of Figure 1		1		µs
t_f	Fall time						

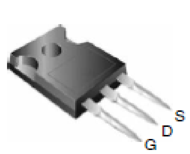
APPENDIX B
Data Sheet for MOSFET IRFP460

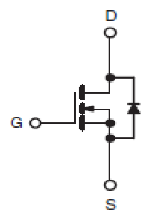
IRFP460, SiHFP460
Vishay Siliconix

Power MOSFET

PRODUCT SUMMARY		
V_{DS} (V)	500	
$R_{DS(on)}$ (Ω)	V_{GS} = 10 V	0.27
Q_g (Max.) (nC)	210	
Q_{gs} (nC)	29	
Q_{gd} (nC)	110	
Configuration	Single	

TO-247





N-Channel MOSFET

FEATURES

- Dynamic dV/dt Rating
- Repetitive Avalanche Rated
- Isolated Central Mounting Hole
- Fast Switching
- Ease of Paralleling
- Simple Drive Requirements
- Lead (Pb)-free Available

Pb Available
RoHS* COMPLIANT

DESCRIPTION

Third generation Power MOSFETs from Vishay provide the designer with the best combination of fast switching, ruggedized device design, low on-resistance and cost-effectiveness.
The TO-247 package is preferred for commercial-industrial applications where higher power levels preclude the use of TO-220 devices. The TO-247 is similar but superior to the earlier TO-218 package because its isolated mounting hole. It also provides greater creepage distances between pins to meet the requirements of most safety specifications.

ORDERING INFORMATION	
Package	TO-247
Lead (Pb)-free	IRFP460PbF
	SiHFP460-E3
SnPb	IRFP460
	SiHFP460

ABSOLUTE MAXIMUM RATINGS T_C = 25 °C, unless otherwise noted

PARAMETER			SYMBOL	LIMIT	UNIT
Drain-Source Voltage			V_{DS}	500	V
Gate-Source Voltage			V_{GS}	± 20	V
Continuous Drain Current	V_{GS} at 10 V	T_C = 25 °C	I_D	20	A
		T_C = 100 °C		13	
Pulsed Drain Current[a]			I_{DM}	80	
Linear Derating Factor				2.2	W/°C
Single Pulse Avalanche Energy[b]			E_{AS}	960	mJ
Repetitive Avalanche Current[a]			I_{AR}	20	A
Repetitive Avalanche Energy[a]			E_{AR}	28	mJ
Maximum Power Dissipation	T_C = 25 °C		P_D	280	W
Peak Diode Recovery dV/dt[c]			dV/dt	3.5	V/ns
Operating Junction and Storage Temperature Range			T_J, T_{stg}	- 55 to + 150	°C
Soldering Recommendations (Peak Temperature)	for 10 s			300[d]	
Mounting Torque	6-32 or M3 screw			10	lbf · in
				1.1	N · m

Notes
a. Repetitive rating; pulse width limited by maximum junction temperature (see fig. 11).
b. V_{DD} = 50 V, starting T_J = 25 °C, L = 4.3 mH, R_G = 25 Ω, I_{AS} = 20 A (see fig. 12).
c. $I_{SD} \leq$ 20 A, dI/dt $\leq$ 160 A/μs, $V_{DD} \leq V_{DS}$, $T_J \leq$ 150 °C.
d. 1.6 mm from case.

* Pb containing terminations are not RoHS compliant, exemptions may apply

THERMAL RESISTANCE RATINGS				
PARAMETER	**SYMBOL**	**TYP.**	**MAX.**	**UNIT**
Maximum Junction-to-Ambient	R_{thJA}	-	40	°C/W
Case-to-Sink, Flat, Greased Surface	R_{thCS}	0.24	-	
Maximum Junction-to-Case (Drain)	R_{thJC}	-	0.45	

SPECIFICATIONS $T_J = 25$ °C, unless otherwise noted						
PARAMETER	**SYMBOL**	**TEST CONDITIONS**	**MIN.**	**TYP.**	**MAX.**	**UNIT**
Static						
Drain-Source Breakdown Voltage	V_{DS}	$V_{GS} = 0$ V, $I_D = 250$ µA	500	-	-	V
V_{DS} Temperature Coefficient	$\Delta V_{DS}/T_J$	Reference to 25 °C, $I_D = 1$ mA	-	0.63	-	V/°C
Gate-Source Threshold Voltage	$V_{GS(th)}$	$V_{DS} = V_{GS}$, $I_D = 250$ µA	2.0	-	4.0	V
Gate-Source Leakage	I_{GSS}	$V_{GS} = \pm 20$ V	-	-	± 100	nA
Zero Gate Voltage Drain Current	I_{DSS}	$V_{DS} = 500$ V, $V_{GS} = 0$ V	-	-	25	µA
		$V_{DS} = 400$ V, $V_{GS} = 0$ V, $T_J = 125$ °C	-	-	250	
Drain-Source On-State Resistance	$R_{DS(on)}$	$V_{GS} = 10$ V; $I_D = 12$ A[b]	-	-	0.27	Ω
Forward Transconductance	g_{fs}	$V_{DS} = 50$ V, $I_D = 12$ A[b]	13	-	-	S
Dynamic						
Input Capacitance	C_{iss}	$V_{GS} = 0$ V, $V_{DS} = 25$ V, f = 1.0 MHz, see fig. 5	-	4200	-	pF
Output Capacitance	C_{oss}		-	870	-	
Reverse Transfer Capacitance	C_{rss}		-	350	-	
Total Gate Charge	Q_g	$V_{GS} = 10$ V; $I_D = 20$ A, $V_{DS} = 400$ V see fig. 6 and 13[b]	-	-	210	nC
Gate-Source Charge	Q_{gs}		-	-	29	
Gate-Drain Charge	Q_{gd}		-	-	110	
Turn-On Delay Time	$t_{d(on)}$	$V_{DD} = 250$ V, $I_D = 20$ A, $R_G = 4.3$ Ω, $R_D = 13$ Ω, see fig. 10[b]	-	18	-	ns
Rise Time	t_r		-	59	-	
Turn-Off Delay Time	$t_{d(off)}$		-	110	-	
Fall Time	t_f		-	58	-	
Internal Drain Inductance	L_D	Between lead, 6 mm (0.25") from package and center of die contact 	-	5.0	-	nH
Internal Source Inductance	L_S		-	13	-	
Drain-Source Body Diode Characteristics						
Continuous Source-Drain Diode Current	I_S	MOSFET symbol showing the integral reverse p - n junction diode 	-	-	20	A
Pulsed Diode Forward Current[a]	I_{SM}		-	-	80	
Body Diode Voltage	V_{SD}	$T_J = 25$ °C, $I_S = 20$ A, $V_{GS} = 0$ V[b]	-	-	1.8	V
Body Diode Reverse Recovery Time	t_{rr}	$T_J = 25$ °C, $I_F = 20$A, dI/dt = 100 A/µs[b]	-	570	860	ns
Body Diode Reverse Recovery Charge	Q_{rr}		-	5.7	8.6	µC
Forward Turn-On Time	t_{on}	Intrinsic turn-on time is negligible (turn-on is dominated by L_S and L_D)				

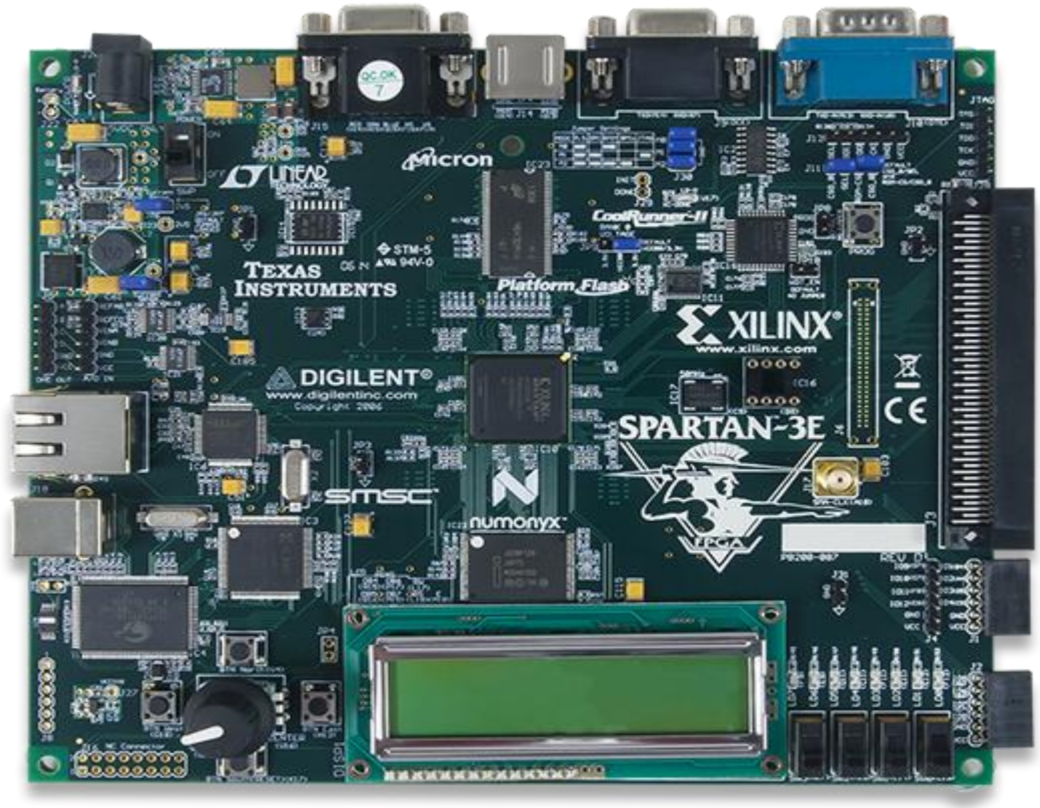
Notes

a. Repetitive rating; pulse width limited by maximum junction temperature (see fig. 11).

b. Pulse width ≤ 300 µs; duty cycle ≤ 2 %.

APPENDIX C

KIT DETAILS OF SPARTAN 3E



Product Description

The Spartan®-3E Starter Board provides a powerful and highly advanced self-contained development platform for designs targeting the Spartan-3E FPGA from Xilinx®. It features a 500K gate Spartan-3E FPGA with a 32-bit RISC processor and DDR interfaces.

The board also features a Xilinx Platform Flash, USB, and JTAG parallel programming interfaces with numerous FPGA configuration options via the onboard Intel® StrataFlash and STMicroelectronics® Serial Flash. The board is fully compatible with all versions of the Xilinx ISE® tools, including the free WebPACK™. The board ships with a power supply and USB cable for programming so designs can be implemented immediately with no hidden costs.

Stats:

Processor/IC: **Xilinx Spartan-3E** (500K gates) XC3S500E FPGA

Connector(s):

- 100-pin Hirose FX2 connector
- Three 6-pin Pmod ports
- DB15HD VGA
- PS/2 keyboard
- Two DB9 RS-232 connectors
- RJ-45 Ethernet
- 16-pin header for optional LCD modules
- SMA connector for high-speed clock input

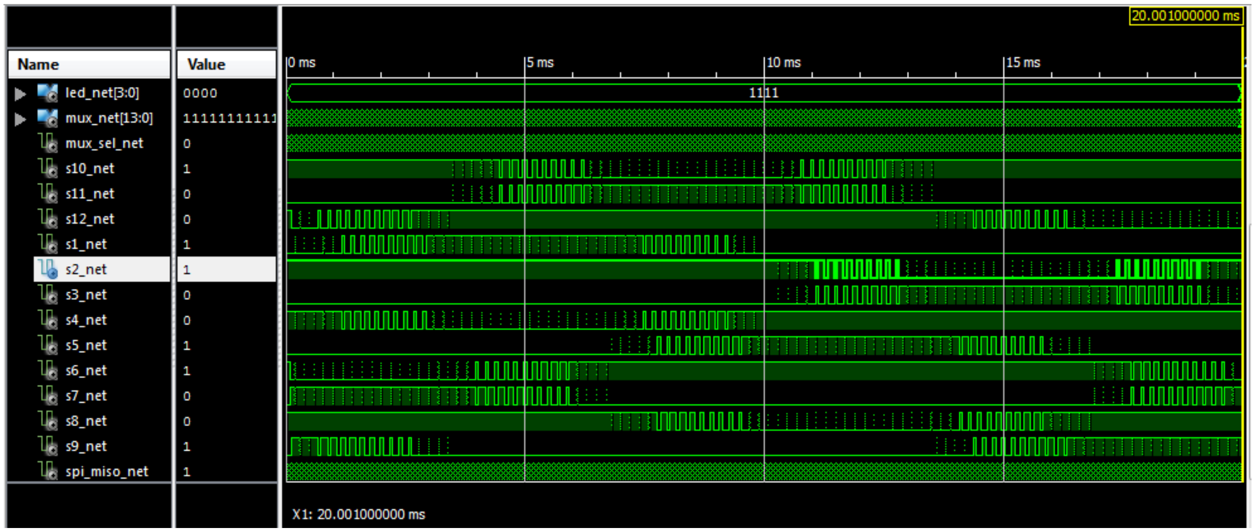
Programming: JTAG programming via on-board USB2 port; JTAG & SPI Flash programming with parallel or USB JTAG cable; numerous additional configuration options

Features:

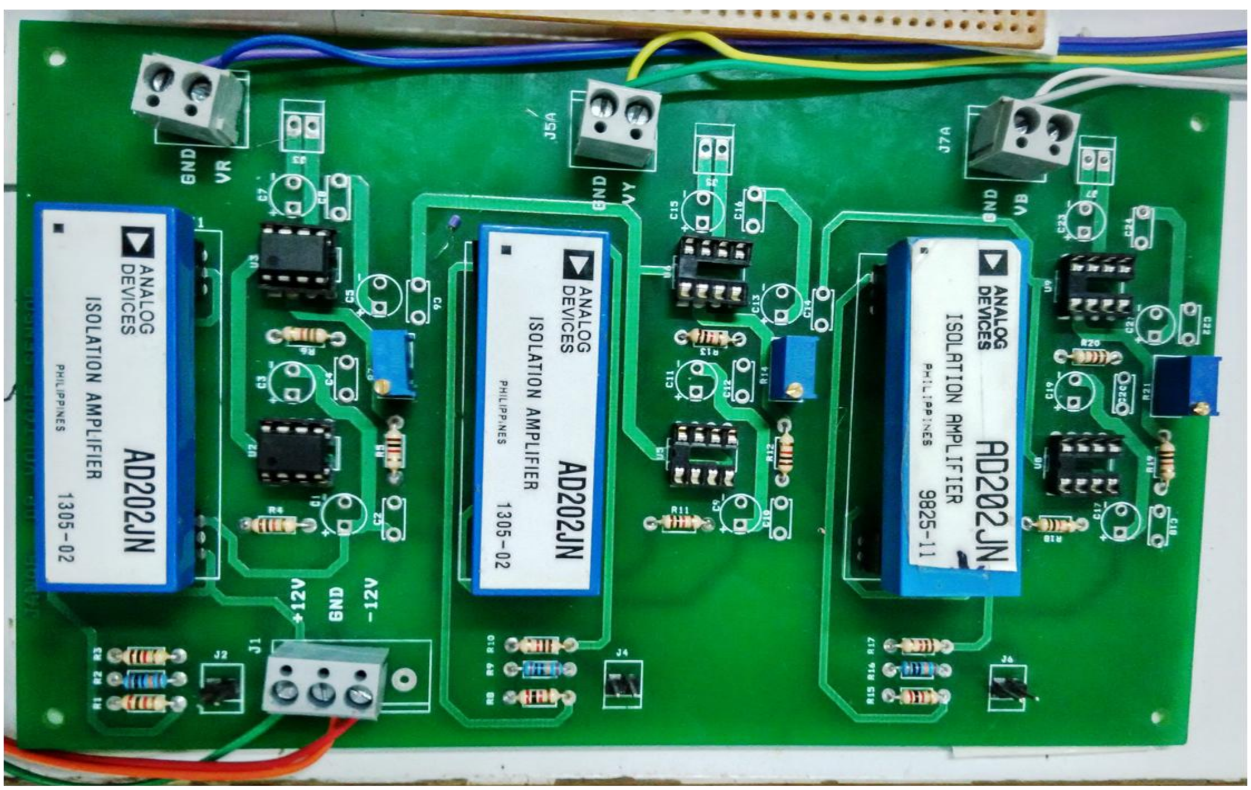
- **Xilinx Spartan-3E** (500K gates) XC3S500E FPGA
- Xilinx XCF04 Platform Flash for storing FPGA configurations
- Texas Instruments TPS75003 Triple-Supply Power Management IC
- JTAG & SPI Flash programming with parallel or USB JTAG cable
- Linear Technology Power Supplies
- 64MB Micron® DDR SDRAM
- 16MB Numonyx StrataFlash™
- 2MB ST Microelectronics Serial Flash
- JTAG programming via on-board USB2 port
- Numerous additional configuration options
- SMSC LAN83C185 Ethernet PHY
- PS/2 keyboard
- RJ-45 Ethernet
- 16-pin header for optional LCD modules
- SMA connector for high-speed clock input
- Two DB9 RS-232 connectors
- 100-pin Hirose FX2 connector

APPENDIX D

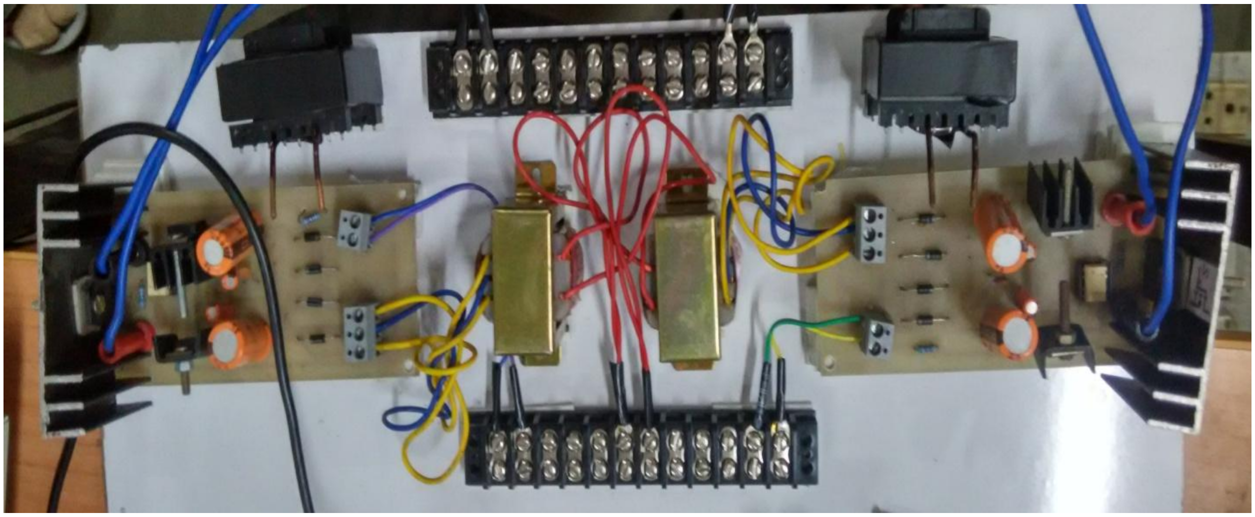
Hardware Diagrams



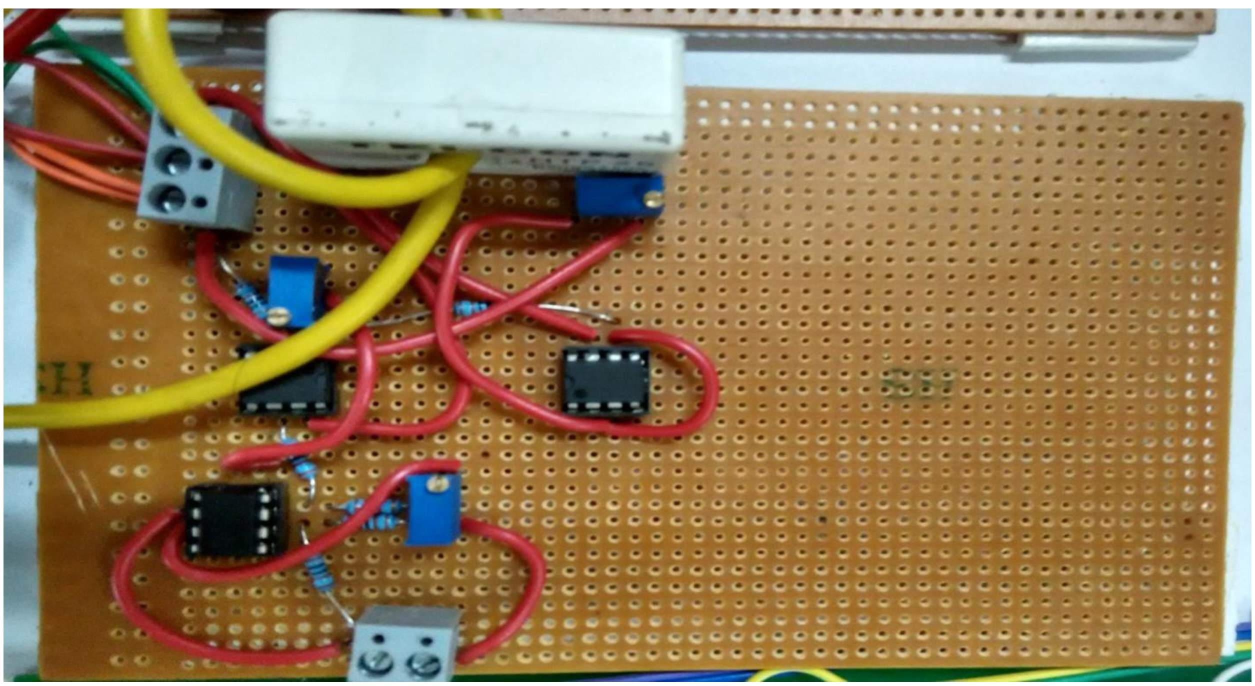
FPGA Pulses



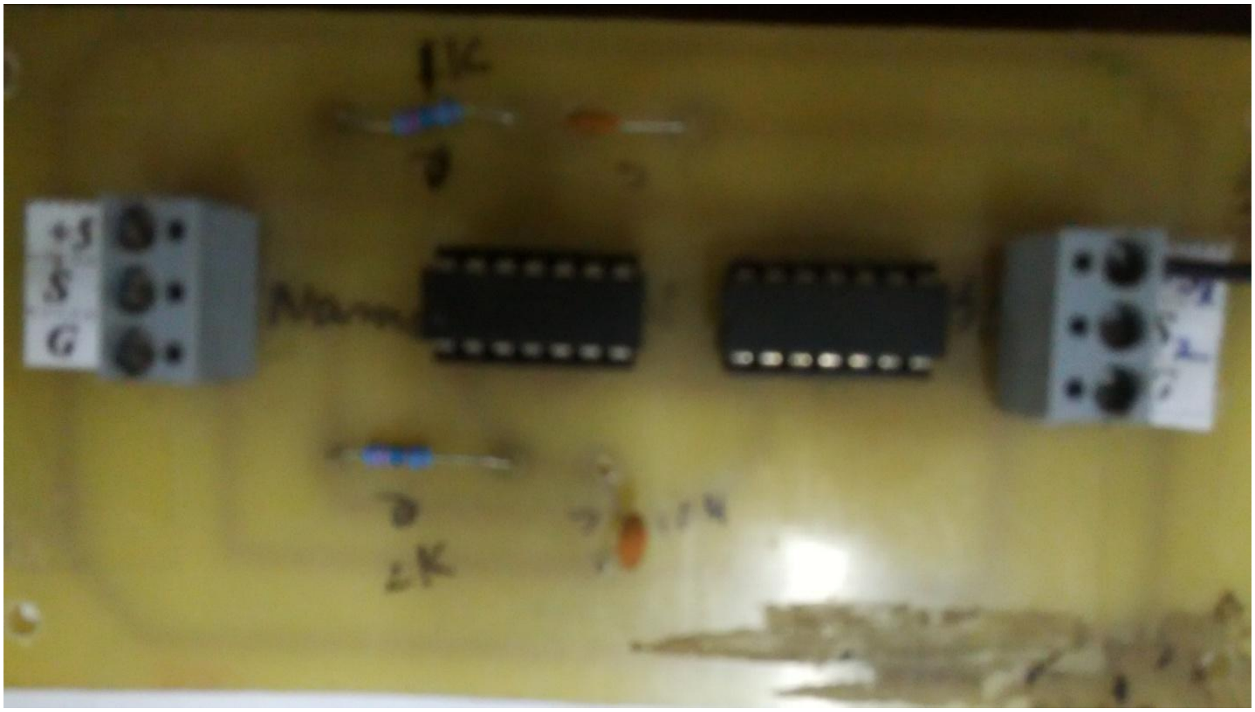
Voltage Sensor



Boost converter circuit



Current sensor



Dead band circuit